LIMESTONE CONCRETE

By the same Author

REINFORCED CONCRETE ROADS

PRACTICAL CONCRETE

PROPERTIES OF CONCRETE

LIMESTONE CONCRETE

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PREFACE

THE consumption of cement in this country before the war was in the neighbourhood of 7,000,000 tons per annum. Estimating on an average mix of 4 : 2 : 1 by weight, this means that 42,000,000 tons of aggregate will be used with the cement. It is clear that with such a large market many people will be interested in the sale of aggregates. Realising the importance of this market, organisations have been formed with the idea of investigating the possibilities of various types of material, and in this connection The British Limestone (Roadstone) Federation intends to consider fully the use of limestone as an aggregate for concrete. This is an important point, as, when the leaders of an industry are studying their products with the idea of improving them from the consumer's point of view, the purchaser can be assured of service and help in his problems.

Naturally enough, the producers of limestone aggregates can be expected to bring forward the good points of their own products, but it cannot be too strongly emphasised that these good points are based on facts, and are not merely sales talk. The statements can be supported by tests and examples of use under practical conditions. When limestone is referred to in the following text, it is understood that good, hard, structurally sound material is meant.

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CHAPTER I

REGULATIONS

In the past, one or two regulations have prohibited the use of limestone as a concrete aggregate, but there have been many which indicated quite clearly that limestone has been considered entirely acceptable, and the following extracts may be of interest.

1909.—Interim Report of the Special Commission on Concrete Aggregates, appointed by the British Fire Prevention Committee, published in *Concrete and Constructional Engineering*, January 1909.

Sandstones, limestones, quartzites and rocks of similar character for use as concrete aggregates shall be dense, uniform, and homogeneous in structure and composition. They shall have small, even grains, and crystalline texture. (This is not intended to exclude oolites otherwise suitable.) Fractures shall be clean and free from large flaws. The weight of the material shall not be less than 130 lbs. per cubic foot, nor its crushing strength less than 200 tons per square foot, and it shall not absorb more water than 8 per cent. of its weight after immersion for 24 hours. The aggregate after preparation shall be free from all dirt, decomposed rock, argillaceous and organic material.

1924.—Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete (U.S.A.).

Coarse aggregate shall consist of crushed stone, gravel, or other approved inert materials with similar characteristics, or combinations thereof, having clean, hard, strong, durable, uncoated particles free from injurious amounts of soft, friable, thin, elongated or laminated pieces, alkali, organic or other deleterious matter.

1928.—Proposed Standard Building Regulations for Reinforced Concrete, American Concrete Institute.

Concrete aggregates shall consist of natural sands and gravels, crushed rock, crushed air-cooled blast-furnace slag, or other inert materials having clean, uncoated grains of strong and durable minerals.

1930.—" Specifications for the Small Job ", by S. C. Hollister, American Concrete Institute.

Coarse aggregates shall consist of crushed stone, gravel, or blast-furnace slag, having clean, hard, strong, durable, uncoated particles free from injurious amounts of soft, friable, thin, elongated, or laminated pieces, alkali, organic or other deleterious matter.

1934.—Code of Practice for Reinforced Concrete, prepared by a Committee of the Building Research Board of the Department of Scientific and Industrial Research. This Report was issued after careful consideration of all available information, and it is worth while to give the regulation referring

A*

to aggregates to make it clear that good limestone is no longer a prohibited material.

(*a*) *General (Permissible Materials)*.—Aggregates shall consist of natural sands and gravels, crushed stone, or other suitable material. They shall be hard, strong and durable, and shall be clean and free from clay films and other adherent coatings.

(*b*) *Prohibited Materials and Impurities.* Aggregates shall contain no deleterious material in sufficient quantity to reduce the strength or durability of the concrete, or to attack the steel reinforcement. Under this clause prohibited materials include the following:

(i) Coal and coal residues, including clinkers, ashes, coke, breeze, pan breeze, slag and other similar material.
(ii) Copper slag, forge breeze, dross and other similar material.
(iii) Soluble sulphates, including gypsum and other similar material.
(iv) Coarse aggregate of a porous nature if the percentage increase in weight of a representative dry sample of the material exceeds 10 per cent. after immersion in water for 24 hours, excepting as permitted under (*c*).
(v) Fine aggregate containing organic material in sufficient quantity to show a darker colour than the standard colour when tested according to the method given in Appendix (II).
(vi) Fine or coarse aggregate containing clay lumps exceeding 1 per cent. by weight.
(vii) Fine aggregate containing material removable by decantation, according to the standard method given in Appendix (III), exceeding 3 per cent. by weight.

1937.—Specification Clauses for General Concrete Work, Cement and Concrete Association.

Coarse aggregate to consist of gravel, crushed stone or other suitable material, the particles to be hard, durable, clean and free from crusher dust, or other adherent coatings. The particles to range in size from fine to coarse within the limits indicated in Appendix B.

1938.—Code of Practice for the Design and Construction of Reinforced-Concrete Structures for the Storage of Liquids, prepared by The Institution of Civil Engineers.

(*a*) *General (Permissible Materials).* Aggregates shall consist of natural sands and gravels, crushed stone, or other suitable material. They shall be hard, strong and durable, and shall be clean and free from clay films and other adherent coatings.

(*b*) *Prohibited Materials and Impurities.* Aggregates shall contain no deleterious material in sufficient quantity to reduce the strength, durability or impermeability of the concrete, or to attack the steel reinforcement. Under this clause, prohibited materials include the following :—

(i) Coal and coal residues, including clinkers, ashes, coke, breeze, pan breeze, slag and other similar material.
(ii) Copper slag, forge breeze, dross and other similar material.
(iii) Aggregates containing water-soluble sulphur trioxide (SO_3) in excess of 0·1 per cent.
iv) Coarse aggregate of a porous nature, if the percentage increase in weight of a representative dry sample of the material exceeds

8 per cent. after immersion in water when tested as laid down in Appendix 1.

1940.—British Standard Specification for Natural Aggregates, No. 882—1940.

Aggregate shall consist of naturally occurring sand, gravel, or stone, whole or crushed, or a combination thereof. It shall be hard, strong, durable, clean and free from adherent coatings.

The eight references show that limestone is acceptable as a coarse aggregate both in this country and in U.S.A. It is understood, of course, that structurally sound material of approved quality will be used.

CHAPTER II

PROPERTIES OF AGGREGATES

It will be useful to refer to the various properties of aggregates and to see how limestone complies with them.

Specifications. Not only from the point of view of the consumer, but also from that of the producer, good specifications for aggregates are desirable. The producers of limestone are in a position to supply any grading in any quantity at any time to comply with any type of fair specification. This is important to the engineer and the contractor who wish to be certain of as many of the "variables" as possible. A source of aggregate which can be relied upon to supply material up to specification standard at all times is most desirable, and once an engineer has found such a supply, he will be the first to appreciate its value.

If anyone requires a certain grading which is not being produced commercially by a quarry in his vicinity, he should discuss the matter and see if it is not possible to substitute an alternative grading at a much lower cost. Should this course not be deemed advisable, special gradings can often be arranged for at very little or no extra cost.

Cost of Materials. It is always difficult to give costs which can be used as a guide, but for our present argument approximate figures can be used. Assuming that the average concrete is a 4 : 2 : 1 mix by weight, and that the prices are 12*s.* 6*d.* per ton for coarse aggregate, 10*s.* per ton for fine aggregate, and 50*s.* per ton for cement, it is clear that the aggregates cost more than the cement. This is a very good reason why the importance of aggregates should be appreciated. Some people are apt to think that once they have bought a good cement they can use almost anything with it to make concrete. Good aggregate not only helps to make good concrete, but results in lowering the cement content, thus giving a concrete which is actually cheaper per cubic yard than one made with an inferior aggregate.

Nomenclature. Probably in no other industry is the misuse of names so prevalent and misleading as in the quarrying industry. For instance, "granite" has come to be recognised as a household word for a good, hard aggregate, and therefore people who have had

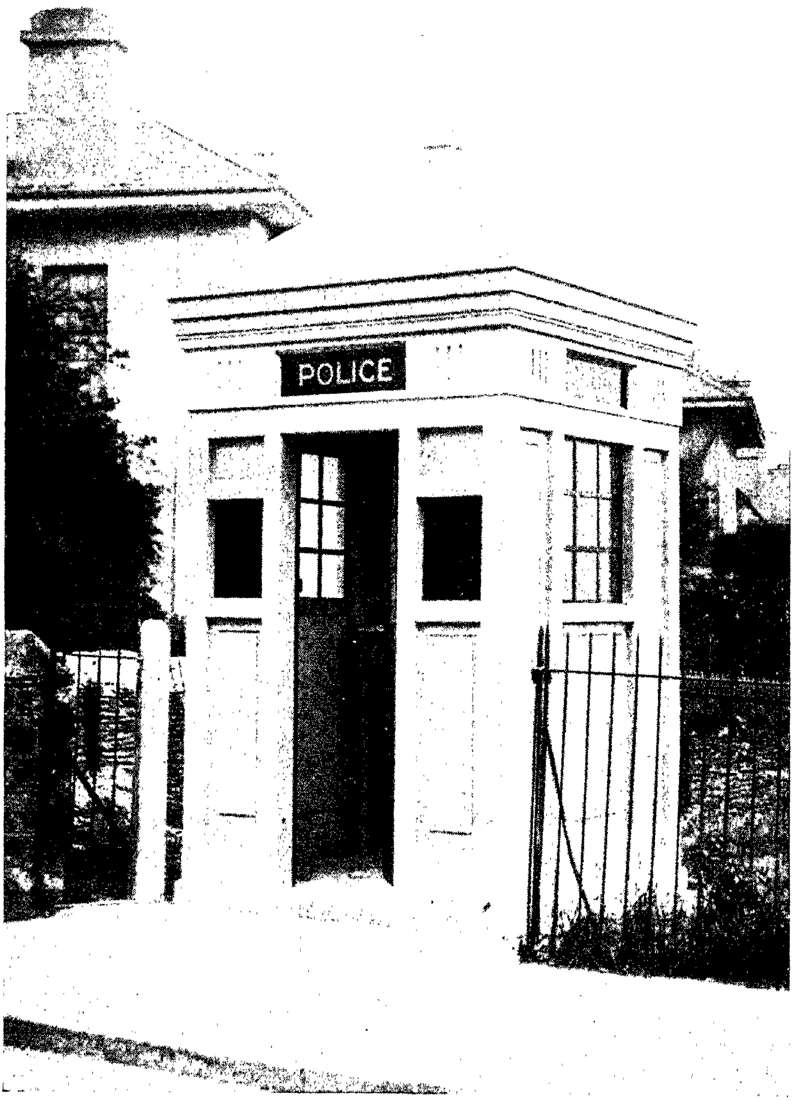


Fig. 1.—Precast Concrete Police Kiosk made with Limestone Aggregate.

[*Facing p.* 4.

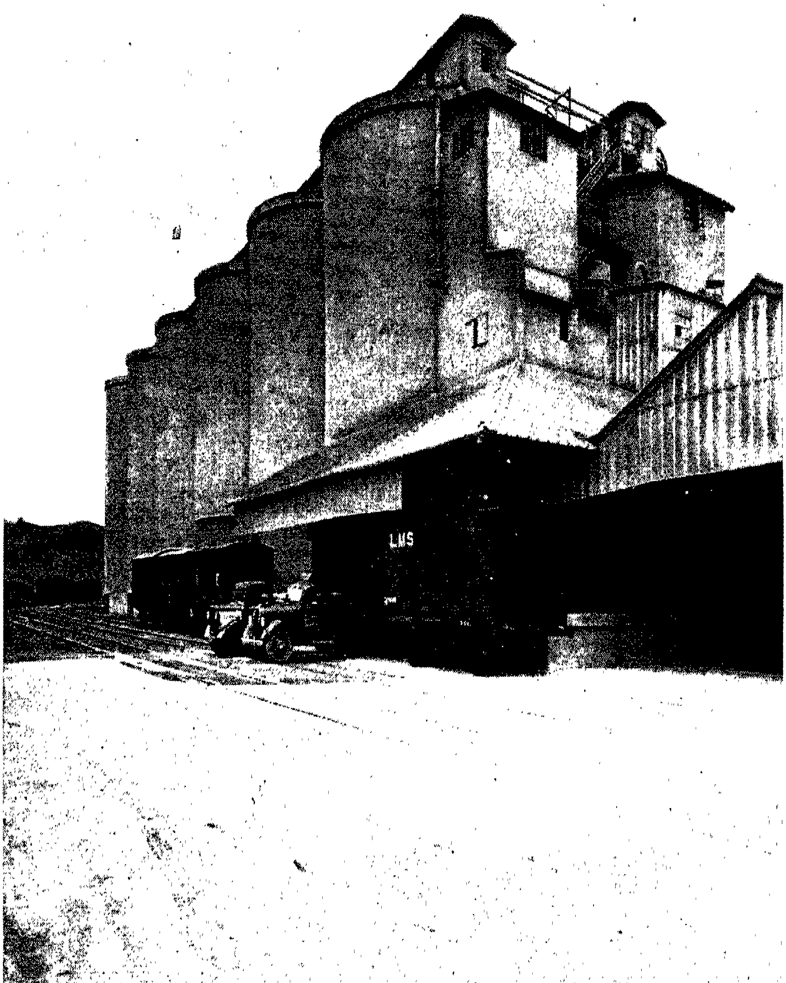


Fig. 2.—Cement Silos at Hope built with Limestone Aggregate.

suitable aggregates to sell have succumbed to the temptation of calling their material "granite". This is bad enough in itself, but there is another and more serious objection, namely, that aggregates which are not called "granite" have been assumed to be inferior. It cannot be stressed too much that this point of view is entirely erroneous, and whilst not detracting from the admittedly good qualities of granite, it is easily demonstrated that there are other natural stones not in the granite "family" which can do all that is required of them as aggregates. Good limestones are in this class, and the members of the British Limestone (Roadstone) Federation market their material as limestone, in the knowledge that they have an excellent material to offer to the building industry—certainly one which does not need to be disguised under another name.

Grading. It is well known that the grading of an aggregate is of prime importance, and the limestone quarry owners are prepared to supply their materials to the grading which the engineer needs. This is a great advantage, as it means that the user can assume as constant a factor which far too often is extremely variable. In fact, the influence of the aggregate is of such importance that engineers who are aware of the possibilities will be quite prepared to pay a premium for a high-class material. The cost of an aggregate should not be measured by its cost at the quarry, or at the point of delivery, but by its cost per cubic yard of concrete per unit of strength.

A modern specification gives limits for the size of aggregate, and whilst it is not always possible or advisable to fix the grading sieve by sieve, there is no doubt that general indications have shown that the following is satisfactory for coarse aggregate:

Maximum size $\frac{3}{4}$ in. (or other value).
95 per cent. to pass $\frac{3}{4}$-in. screen.
Not more than 10 per cent. to pass $\frac{3}{16}$-in. screen.
To be uniformly graded within these limits.

Limestone can be supplied to this and similar specifications—B.S. 882, for instance.

For most jobs in this country the aggregates are supplied in two gradings only, i.e., coarse and fine. It will often be found an advantage, however, to supply the coarse aggregate in two or even three gradings so that they can be mixed together in their correct proportions on the site. This may cost a little more, but the extra charge would be more than recovered by the improved quality of the concrete. This is one of the many factors which call

for close co-operation between engineer, contractor, and producer. A lorry load of aggregate, varying in size from 1 in. to $\frac{3}{16}$ in., is going to separate, and unless the whole of it is remixed (and it very rarely is), the segregation will result in uneven concrete. The use of separated sizes seems to be almost a foregone conclusion for concrete work in the near future. The producers of limestone have appreciated this point, and the material is available in separated sizes.

Shape of Particles. Whilst the presence of flat and elongated pieces is not usually as serious as is sometimes believed, it seems reasonable to assume that a concrete without any excessively flat pieces is better than one containing them. Limestone is free from this defect, and it will be found that none of the particles has an excessively flat shape.

Soft Particles. Some of the aggregates on the market to-day contain a fair proportion of soft particles, which, in many types of work, are apt to cause trouble. A good, hard limestone is free from this defect. Whilst this point is not always given the attention it deserves, it is one which cannot be overlooked when high-class concrete is desired.

Cleanliness. A far too prevalent occurrence is the presence of excessive deleterious organic matter in the aggregate. This, of course, applies to some classes of aggregates and not to others. Limestone is free from this defect.

Chemical Activity. One of the essential requirements of an aggregate is that it must be *inert* in the presence of water. Many of the "artificial" aggregates are not inert. Slags may or may not be free from harmful amounts of injurious constituents. Several concrete failures have been traced to the presence of an excessive quantity of "sulphide" in slag used as aggregate. Certain types of broken brick have been known to cause serious "spalling" in the concrete. Cinders and clinkers have caused failures of varying degree.

In general, it is assumed that all "natural" aggregates are inert; although a few misguided people have the idea that limestone will have some chemical action with the cement. This, of course, is nonsense; there is no chemical action at all. There are a few natural aggregates, referred to briefly as spar, dolerite and opal, which may not be inert, but limestone is certainly not one of them. Some spars contain deleterious amounts of zinc. Many of the dolerites form quite satisfactory aggregates, but certain of them contain mineral constituents which produce expansion in the

hardened concrete. Certain aggregates with high-alkali (the word "alkali" is used to denote the common alkali-metals, sodium and potassium) cement may lead to cracking. One combination producing this troublesome reaction is opal in the aggregate with the alkalies in the cement.

LIMESTONE "SAND" AND LIMESTONE "DUST" FOR MORTAR AND CONCRETE

THERE are many engineers who would not use stone "dust" for cement mortar or concrete, and they would make the decision without bothering to find out just what the "dust" was, and whether their decision was justified.

Limestone Sand. Perhaps part of the trouble is due to the slackness of the quarrying industry in allowing the word "dust" to cover a wide range of materials. For instance, one producer assumes $\frac{3}{16}$ in. and down stone to be dust, and calls it just that; whereas when another producer talks of dust he means material passing the 200-mesh sieve. There are other gradings, between these two extremes, all assumed to be in the same classification. It is suggested, therefore, that the word "dust" should only be used for that portion of the limestone which would pass a 200-mesh sieve. Material which is $\frac{3}{16}$ in. and down, or $\frac{1}{8}$ in. and down, should be given another and more appropriate designation, such as "fine stone", "stone sand" or "fine stone aggregate". In this book it will be referred to as "limestone sand".

Specifications for Fine Aggregate. In the writer's opinion, most modern specifications for fine aggregates for concrete work are too strict, as far as the very fine material is concerned. For instance, in the British Standard Specification (A.R.P. Series) for "Aggregates for Concrete Shelters Constructed in Situ", issued in July 1939, it states that the fine aggregate "shall be well graded from $\frac{3}{16}$ in. to 100 mesh". There is no allowance for a reasonable amount of material passing the 100 mesh, apart from the statement that the "fine aggregate shall not contain silt in excess of 3 per cent. by weight". Surely this specification is far too strict for most practical jobs. In any commercial aggregate it is almost certain that there will be a small percentage passing the 100 mesh, and there should be some tolerance. That this is true in the case of limestone is shown by the following tests.

The idea behind these specification restrictions is that very fine material, or "dust", is harmful. But is it as harmful as has

generally been supposed? Or, in limited quantities, is it harmful at all?

Two points arise:

1. Is limestone sand satisfactory as a fine aggregate?
2. What quantity of limestone dust is permissible?

The writer will not attempt to answer the second question completely, but there seems no doubt about the answer to the first.

Objections. Objections which have been raised to the use of limestone sand and the inclusion of limestone dust are:

1. They react chemically with the cement.
2. They reduce the strength.
3. They reduce the durability of the finished product.
4. They increase the tendency to crack and craze.
5. They decrease workability.
6. They increase absorption and porosity.

The first objection is entirely without foundation, and it can be stated definitely that limestone, no matter what the size of the particles, does *not* react chemically with the cement (see Chapter II). As for the other objections, they are largely answered by the following notes.

Limestone for Products. At the 1927 Convention [1] of the American Concrete Institute, several products manufacturers referred to the advantage of adding a small proportion of limestone screenings to the mix.

W. H. Warford stated that when using an economic mix of sand and gravel it was found impossible to remove blocks from the machine without breakage. The addition of fine limestone to the mix corrected the difficulty.

B. Wilk said:

> At our plant we could not get a really economical mix with the available sand and gravel, even though we used an almost theoretically perfect grading. We found that, even with an experienced man and good operators, blocks made exclusively of sand and gravel in a really lean mix would not stand up. The blocks would fall down on being taken from the machine. By substituting one-third limestone screenings of somewhat similar grading to the sand and gravel, except that 8 per cent. of the limestone passed a 100-mesh sieve, the blocks stood up satisfactorily and could be readily carried away from the machine.

L. Peyton stated that he found the addition of limestone screenings added to workability, allowed the particles to slip into place easily, sealed small pores, and allowed more water to be used,

while the block could still be removed from the machine without breakage.

Limestone Improves Many Properties. Additional evidence of the same kind was given in an article [2] which appeared two years later, as will be seen by the following extract.

Through several years of experimenting it was found that substituting limestone for a portion of the sand lowered the absorption and increased the compressive strength. Between 5 and 10 per cent. of this limestone passed the 100-mesh sieve and undoubtedly this fine material united with the cement to form an abundance of paste which thoroughly coated each and every particle of the aggregate which in turn had a sort of lubricating effect on the mix, producing a denser concrete having a higher compressive strength.

The above statement is verified in the Portland Cement Association booklet on *The Manufacture of Concrete Masonry Units*, which reads as follows:

> In a recent series of tests on tamped concrete block, two varieties of fine aggregate containing relatively large percentages of dust finer than the 100-mesh sieve gave unexpectedly high strengths. Apparently a certain portion of very fine materials results in greater workability and increased strength.

The effect of the limestone is more noticeable in leaner mixes and this ought to convince the most sceptical that even a good mix can be improved by the addition of limestone although it does not contain a large amount of fine material. Manufacturers of precast tanks, vats, septic tanks, sewer pipes, etc., which have to withstand hydrostatic tests, will find the addition of limestone very beneficial.

Limestone and Sand. In spite of evidence of this kind, engineers, products manufacturers and other interested parties in this country continued to prohibit the use of limestone sand and limestone dust. It seemed to the writer that some evidence of the behaviour of these materials in this country should be obtained. But it was difficult, owing to the above-mentioned objections. In 1926, 1927 and 1928 he obtained some rather startling test results, but unfortunately the figures are not now available. However, in 1936 there was an opportunity to compare limestone sand and ordinary sand in concrete.

Four gradings of limestone were submitted, and were found to have the following sieve analyses:

	A Per cent.	B Per cent.	C Per cent.	D Per cent.
Retained on 100-mesh sieve	100·0	100·0	98·6	81·8
" " 52 " "	100·0	100·0	97·6	67·0
" " 25 " "	100·0	100·0	96·8	47·0
" " 14 " "	100·0	100·0	93·6	20·6
" " 7 " "	100·0	100·0	61·4	Nil
" " $\frac{3}{16}$-in. mesh sieve	100·0	81·5	Nil	
" " $\frac{3}{8}$ " " "	98·5	3·0		
" " $\frac{3}{4}$ " " "	3·8	Nil		
Fineness modulus	7·023	5·845	4·480	2·164
Material washed through 170-mesh sieve				19·2

It will be seen that the fine material (sample D) contained about one-fifth passing the 170 mesh. Most engineers would condemn this out of hand, stating that the strength of the concrete would be reduced appreciably by such a large quantity of dust. A 6-in. cube was made, using equal parts by volume of A, B, C and D, and a corresponding cube was made with the same mix except that Trent sand was substituted for limestone D. The results are given below, the cubes being broken at 7 days.

Mix	Weight of Cube lb.	Crushing Stress lb. per sq. in.
No. 1.—Equal parts of A, B, C and D mixed together. 4 : 1 mix. 1 in. slump	18·7	3795
No. 2.—4 : 1 mix as above, but Trent sand substituted for limestone D	18·3	3300

It is realised that sweeping conclusions cannot be drawn from the results of single cubes, but unfortunately there was not sufficient material to make more extensive tests.

Cheddar Reservoir. Some engineers prefer tests from a job in progress. Limestone, both coarse and fine, was used in the construction of the Cheddar Reservoir, and the test results obtained may surprise those who consider limestone unsuitable for concrete.

The proportions [3] for the whole of the concrete with the exception of certain pre-cast blocks were 5 : 3 : 1. The aggregate used was $1\frac{1}{2}$ in. to $\frac{3}{16}$ in. limestone, and the sand content a mixture of 50 per

cent. Holm sand and 50 per cent. limestone crushing. Two gradings of fine limestone were used:

1. Sand—mainly $\frac{1}{4}$ in. to $\frac{1}{20}$ in., but described as " $\frac{1}{8}$-in. limestone ".
2. Dust—half of which passed the 180 mesh.

Tensile tests were made varying the proportion of $\frac{1}{8}$ in. and dust, and a comparison was made with Ham River sand; these gave the following results, which were the average of six samples in each case:

Mixture 1	Mixture 2	Mixture 3	Mixture 4
1 cement $1\frac{1}{2}$ dust $1\frac{1}{2}$ limestone	1 cement 1 dust 2 limestone	1 cement 2 dust 1 limestone	1 cement 3 Ham River sand
14 days— 750 lb. per sq. in.	804 lb. per sq. in.	696 lb. per sq. in.	534 lb. per sq. in.
28 days— 792 lb. per sq. in.	833 lb. per sq. in.	747 lb. per sq. in.	553 lb. per sq. in.

Standard percolation tests of the four mixtures were made, the results being:

Mixture 1
14 Days. At 90 lb. the underside of the blocks was a little wet.
28 Days. At 130 lb. slight dampness was apparent on the undersurface of the blocks.

Mixture 2
14 Days. Under-surface became a little damp at 90 lb. per square inch.
28 Days. A small bead of water showed on the underside at 130 lb.

Mixture 3
14 Days. One or two beads of water formed at 60 lb. per square inch.
28 Days. As at 14 days, but with a pressure of 90 lb. per square inch.

Mixture 4
14 Days. A few small beads of water formed at 55 lb. per square inch.
28 Days. At 70-lb. pressure, water appeared on the undersurface.

Limestone Dust in Mortar. The gradation of stone [4] sand greatly influences the workability of concrete made with this material, used as a fine aggregate. If it is too coarse, a " grainy " mix results, which is harsh working and which does not hold the mixing water in place. Fine stone dust greatly adds to the plasticity or workability of an otherwise harsh working mixture and from this standpoint " fines " are desirable. But the question arises: What effect does stone dust have on the physical properties of the concrete? Light is thrown on this question through a preliminary series of tests made in the National Crushed Stone Association laboratory.

Mortars were made up in the proportion of 1 : 2 by weight, using limestone sands having the following gradations :

Total per cent. retained on	Coarse	Medium	Fine
No. 4	0	0	0
8	5	3	0
16	50	38	25
30	70	60	50
50	90	80	70
100	97	93	90
Fineness modulus	3·12	2·74	2·35

To the stone sands of the above gradations, limestone dust passing the No. 200 sieve was added to the amounts of 10, 20, and 30 per cent. by weight of cement, equivalent to 5, 10, and 15 per cent. by weight of sand.

All mortars were mixed to approximately the same consistency as determined by the flow table. Finally, after 28 days' storage in the moist room, the specimens (2-in. cubes) were tested for absorption, crushing strength and resistance to freezing and thawing.

It was found that the finer the sand, the higher is the water-ratio required for equal flow or consistency. However, contrary to the general water-cement ratio strength relationship, higher strengths were obtained with the higher water-cement ratios. Likewise the finest sand produced a more resistant mortar in the freezing and thawing test than the coarsest sand, even though the absorption was at the same time higher with the finer gradations.

10 per cent. of dust by weight of cement (5 per cent. by weight of stone sand) increased the crushing strength and also the durability with all three sand gradations, but 20 per cent. increased the strength and durability only of the coarse and intermediate gradations. Finally, 30 per cent. of dust (15 per cent. by weight of sand) decreased the crushing strength, particularly of the intermediate and fine gradations, and shows no benefit so far as durability is concerned.

It seems reasonable to conclude from these tests that for 1 : 2 mortar a small amount of stone dust passing the No. 200 sieve, up to 5 per cent. by weight of sand, should improve the mortar-making properties of stone sands within the range of gradation shown, but that more than 10 per cent. may be harmful, particularly if the sand has a fine gradation.

If the results are further analysed, the indications from these tests point to the desirability of raising the allowable stone dust

content above that ordinarily allowed by specifications, perhaps up to 15 per cent. passing through the No. 100 sieve.

Dust and Properties of Mortars. Tests were made in the U.S.A. to gain additional information on the effect of various quantities of dust in stone sand on the properties of mortar such as might be used in highway concrete. In his article,[5] Goldbeck stated that the following brief summary of indications from the tests seemed warranted:

1. To maintain a given consistency in mortars containing dust varying in amount from 4 up to 24 per cent., very little increase in water-cement ratio is required.
2. Neither the volume of water released upon settlement of the fresh mortar nor the volumetric shrinkage of the fresh mortar is affected to a significant extent by an increase in dust content up to 24 per cent.
3. Crushing strength of mortar is somewhat decreased with increasing percentages of dust. The crushing strength of the 24 per cent. dust content mortar was 90 per cent. of that containing only 4 per cent. dust.
4. The absorption increases with increasing percentages of dust.
5. The durability seems to be affected to a significant degree by high percentages of dust, far more than can be accounted for by the rather slight increase in water-cement ratio required to maintain the same consistency. It would seem inadvisable to use more than 8 to 10 per cent. of minus No. 100 sieve limestone dust in the stone sand used for concrete to be exposed to the weather.
6. The shrinkage of mortar upon drying out in the air is practically unaffected by the dust content in the sand.

Although the above tests were made on mortar, it is to be expected that concrete will be similarly affected, only to a different extent, and hence these tests are applicable qualitatively to concrete also. Finally, it seems safe for concrete containing 1 : 2 mortar to have at least 8 to 10 per cent. of stone dust passing the No. 100 sieve. Only one limestone sand and dust was used in these tests, and it is not improbable that other sands and dusts might give results varying somewhat from these.

Masonry Mortars. Most natural sands [6] are lacking in enough fine material to make them sufficiently plastic when made into masonry mortars. To overcome this lack of fines, hydrated lime is used as an admixture to Portland cement, or specially designed masonry cements are employed. Tests show that excellent masonry

mortars may be made by the use of Portland cement mixed with fine stone sand containing a large quantity of dust. Frequently, also, stone sand containing a high percentage of dust may be used with very beneficial effects when mixed with natural sand. The following results are illustrative of the above statement:

Proportions by Dry, Loose Volume			Crushing Strength lb. per sq. in. at 28 days
Cement	Stone Sand	River Sand	
1	3	—	5,100
1	—	3	3,970
1	1½	1½	5,870

The gradations of the stone sand and river sand used in the above tests were as follows:—

Sieve No.	Stone Sand	River Sand
	Total per cent. retained	
4	0	0
8	7	9
16	44	22
30	60	39
50	67	86
100	71	100
200	74	100
Loss by washing	18·6	0·3

Roofing Tiles. The following are extracts (11 May, 1939) from a letter received from a company in the Midlands.

We are large makers of concrete roofing tiles, and have many times made samples of roofing tiles with sand to compare them with the tiles we are making with limestone dust. In every case the tile made with limestone dust was far superior in texture and strength to the tile made with clean washed sand. We actually find that we can make a stronger tile with the dust, even when using a less percentage of cement than used with the sand.

The limestone dust is used by us for the manufacture of concrete roofing tiles, to the extent of 50,000 tiles per day, and we claim to make one of the strongest concrete tiles in the country. The dust has the following screen analysis:

Plus 8 mesh	0·55 per cent.
Minus 8, retained 18	31·02 "
" 18, " 36	23·40 "
" 36, " 52	11·62 "
" 52, " 100	20·89 "
" 100	12·52 "

Strength of Mortar. Being more than a little impressed by the results quoted above, and believing that perhaps limestone sand and limestone dust were not as bad as engineers have often been led to believe, the writer obtained a few standard gradings (summer 1939) of materials from different parts of the country and had some mortar briquettes made and tested.

SIEVE ANALYSES

	Material JW Per cent.	Material WC Per cent.	Material BS Per cent.
Residue on 100 sieve	72·0	74·0	Not done
" " 52 "	52·0	62·0	
" " 25 "	26·0	42·8	
" " 14 "	3·4	20·0	
" " 7 "	0·2	0·4	
" " $\frac{3}{16}$ "	Nil	Nil	
Fineness modulus	1·536	1·992	
Material washed through 170 sieve	27·0	26·0	

3 : 1 MORTAR BRIQUETTES AND CUBES TESTED AT 7 DAYS
LB. PER SQUARE INCH

	Reference JW		Reference WC		Reference BS	
Specimen	Limestone	Standard Sand	Limestone	Standard Sand	Limestone	Standard Sand
Briquette	900	710	820	710	830	670
Cube	8,680	8,260	Not enough material for cube		9,400	8,160

Seeing the dust content of these samples, many engineers would condemn them immediately—and very few would expect them to give higher strength results than standard sand. The writer believes that many such limestone sands can be found in this country.

Conclusion. To many people the test results given in this article will be surprising, but to those who have been producing and selling limestone aggregates they are merely part of the evidence which is available to justify the faith they have in their product.

As soon as conditions permit, the British Limestone (Roadstone) Federation propose to carry out an extensive series of tests so that definite information on this country's materials will be available for users.

CHAPTER IV

COMPRESSIVE STRENGTH OF CONCRETE

THE compressive strength of limestone concrete can be made as high as may be required by any modern specification. The strength of the limestone itself is appreciably greater than the strength of the concrete in which it is used, so that the better the cement and the workmanship the higher will be the results. With a very weak aggregate the strength of the concrete may be lower than required, but with good limestone this need never be feared.

Concrete Strengths. Below are given the concrete strengths required by the *Code of Practice* [1]:

Nominal Mix	Proportions Cub. ft. of Aggregate per 112-lb. bag of Cement		Minimum Cube Strength Requirements at 28 Days lb. per sq. in.			
			Ordinary Grade Concrete		High Grade Concrete	
	Fine	Coarse	Preliminary Tests	Works Tests	Preliminary Tests	Works Tests
1 : 1 : 2 . .	$1\frac{1}{4}$	$2\frac{1}{2}$	4,388	2,925	5,625	3,750
1 : 1·2 : 2·4 .	$1\frac{1}{2}$	3	4,163	2,775	5,400	3,600
1 : 1·5 : 3 .	$1\frac{7}{8}$	$3\frac{3}{4}$	3,825	2,550	4,950	3,300
1 : 2 : 4 . .	$2\frac{1}{2}$	5	3,375	2,250	4,275	2,850

Works at Hope. In the construction of the cement works at Hope, Derbyshire, for Messrs. G. & T. Earle, Ltd., limestone produced locally was used for the various structures. Preliminary tests proved beyond doubt that concrete made with limestone as the coarse aggregate had more than sufficient strength. Further investigations as to the possibility of chemical change in the aggregate after a lapse of time were also reassuring, and the work proceeded using limestone obtained on the site and quarried in the ordinary course of preparing the new limestone face for cement manufacture. Cement manufacturers are sufficiently alive to the importance of getting good concrete to avoid the use of aggregates which would affect the stability of their structures in any way.

Viaduct at Hope. The whole of the concrete in the reinforced portion of Edale Viaduct (built in connection with the works mentioned above) was designed for a working stress of 750 lb. per square inch. The mixture adopted was $3\frac{1}{2}$ parts crushed limestone $\frac{3}{4}$ in. to $\frac{1}{8}$ in., $1\frac{3}{4}$ parts Whaley Bridge sand, and 1 part cement, the concrete being mixed as stiffly as possible for the work in hand. The slump for the heavier reinforced concrete members was 2 in., and for the lighter, or more heavily reinforced members, not more than 4 in.

Test cubes were made frequently from the concrete used, and the average compression results in lb. per square inch were:

	7 Days	28 Days	90 Days
2-in. slump	3,707	5,490	6,240
4-in. slump	2,110	4,260	5,100

The following were the factors of safety at different ages:

	7 Days	28 Days	90 Days
2-in. slump	4·9	7·3	8·3
4-in. slump	2·8	5·7	6·8

Mass concrete foundations were placed under the reinforced concrete footings for the piers, the mixture for these being:

10 parts crushed limestone $2\frac{1}{2}$ in. to $\frac{1}{8}$ in.
3 parts crushed limestone $\frac{3}{4}$ in. to $\frac{1}{8}$ in.
2 parts Whaley Bridge sand.
1 part cement.

The strengths obtained with this 15 to 1 concrete, in lb. per square inch, were:

	7 Days	28 Days
1-in. slump	1,390	2,470

Concrete Kerbs. In October 1931 an examination was made of limestone in the following grades: $\frac{3}{4}$ in., $\frac{1}{2}$ in., $\frac{3}{8}$ in., dust. The dust was of good, coarse quality and fairly well graded, but contained 18 per cent. passing the 180-mesh sieve. As the aggregates were required for kerb making, the following mixture was used for compression tests: 1 part $\frac{3}{4}$ in., 1 part $\frac{1}{2}$ in., 1 part $\frac{3}{8}$ in., $\frac{1}{2}$ part dust and 1 part rapid-hardening cement, with the following results:

7 days: 4,725 lb. per sq. in. 28 days: 6,565 lb. per sq. in.

The kerb made with this mixture weighed 143 lb. per cubic foot.

7,000-lb. Concrete. Three samples of crushed limestone were

examined in April 1929, i.e., $\frac{3}{4}$–$\frac{3}{8}$ in., $\frac{3}{8}$–$\frac{1}{8}$ in., $\frac{1}{8}$ in. and down. The sieve analysis of the last sample was as follows:

	Per cent.
Retained on 120-mesh sieve	82·7
" " 50 " "	74·3
" " 30 " "	65·5
" " $\frac{3}{64}$-in. mesh sieve	46·3
" " $\frac{3}{32}$ " " "	29·6
" " $\frac{3}{16}$ " " "	1·2
Material washed through 180-mesh sieve . .	20·0

To get a dense mix the proportions used were 2 parts limestone $\frac{3}{4}$–$\frac{3}{8}$ in., 1 part limestone $\frac{3}{8}$–$\frac{1}{8}$ in., 1 part limestone $\frac{1}{8}$ in. and down, 1 part cement. The slump was 1 in. The following were the results of the cubes:

7 days: 4,155 lb. per sq. in. 28 days: 7,155 lb. per sq. in.

Another Example. Tests were made in December 1933 with 1–$\frac{1}{2}$-in. limestone (fineness modulus, 7·19), sand (fineness modulus, 2·33) and cement, the concrete having a 1-in. slump. The following results were obtained:

	Compressive Stress lb. per sq. in.		
	4 Days	7 Days	28 Days
$3\frac{1}{2}:1\frac{1}{2}:1$ . . .	3,920	4,665	6,905
$3\frac{1}{2}:2:1$	3,420	4,575	6,035

To confirm these figures, check tests were made, with the following results:

	Compressive Stress lb. per sq. in.		
	4 Days	7 Days	28 Days
$3\frac{1}{2}:1\frac{1}{2}:1$ . . .	4,420	5,290	7,155
$3\frac{1}{2}:2:1$	3,735	4,665	6,285

Trench Linings. Some interesting tests were made in April, 1939, to see what results would be obtained with a rather small coarse aggregate. The concrete was composed of $3\frac{1}{2}$ parts limestone $\frac{3}{8}$ in. to $\frac{3}{16}$ in., $1\frac{3}{4}$ parts washed basalt $\frac{1}{8}$ in. and down, and 1 part rapid-hardening cement, by volume. 6-inch cubes were made and

cured in the approved manner, and tested at about 30 days. The detailed results are given below:—

Cube reference	14,090	14,091	14,092
Slump in inches	2	$1\frac{1}{2}$	$2\frac{1}{2}$
Age in days when broken	32	30	28
Weight in lb.	18·2	18·2	18·4
Breaking load in tons	95	101	93
Breaking load in lb. per sq. in.	5,910	6,285	5,785

Comparative Tests. In 1936 comparative tests were made by an independent tester to see if limestone could be considered as good as another aggregate which was recognised as being satisfactory for concrete. The results are given below:

Mix	Compressive Stress lb. per sq. in.	
	7 Days	28 Days
4 cub. ft. limestone chippings ($\frac{3}{4}$–$\frac{3}{16}$ in.), 2 cub. ft. river sand, 90 lb. Portland cement. Gauged with 6·33 per cent. water.	3,937 4,107 3,985	5,410 5,215 5,253
Average	4,009	5,293
4 cub. ft. river shingle ($\frac{3}{4}$–$\frac{3}{16}$ in.), 2 cub. ft. river sand, 90 lb. Portland cement. Gauged with 6·33 per cent. water.	3,565 3,564 3,430	5,418 5,214 4,955
Average	3,519	5,196

Strengths at 28 Days. For convenience, the various strengths obtained in the above tests (6-in. cubes) at 28 days are grouped below:

Proportions by Volume	Slump	Compressive Stress at 28 Days lb. per sq. in.
$3\frac{1}{2} : 1\frac{3}{4} : 1$	2 in.	5,490
$3\frac{1}{2} : 1\frac{3}{4} : 1$	4 in.	4,260
10 : 3 : 2 : 1	1 in.	2,470
$1 : 1 : 1 : \frac{1}{2} : 1$	Stiff mix	6,565
2 : 1 : 1 : 1	1 in.	7,155
$3\frac{1}{2} : 1\frac{1}{2} : 1$	1 in.	7,030
$3\frac{1}{2} : 2 : 1$	1 in.	6,160
$3\frac{1}{2} : 1\frac{3}{4} : 1$	$2\frac{1}{2}$ in.	5,785
4 : 2 : 1	Stiff mix	5,293

Comment. These tests covered a wide range of proportions and were made with different limestones in each case. The results obtained, which are typical of those which can be procured with numerous good limestones, should convince any engineer that limestone is perfectly satisfactory as a coarse aggregate for concrete. There is an ample margin of strength, and there would be no difficulty in complying with any modern specification.

To show just what can be done with limestone aggregate, the following recent results are included. In April 1943 a company of products manufacturers obtained a five-figure result on concrete at 14 days. In January 1944 a similar result was obtained by another products company at 28 days. The cubes were made from the normal run of concrete—not specially prepared mixes. In each case the concrete was vibrated. To get these strengths at such early ages calls for good workmanship, good cement and good aggregates. Brief details of the two cases are given below:

Item	Case 1	Case 2
Cement	Super-rapid-hardening	Rapid-hardening
Age	14 days	28 days
Compressive Stress	10,140 lb. per sq. in.	10,080 lb. per sq. in.
Mix	$1\frac{1}{2} : 1\frac{1}{2} : 1\frac{1}{2} : 1$	$2 : 1\frac{1}{2} : 1 : 1$
Job	Hostels	Sleepers

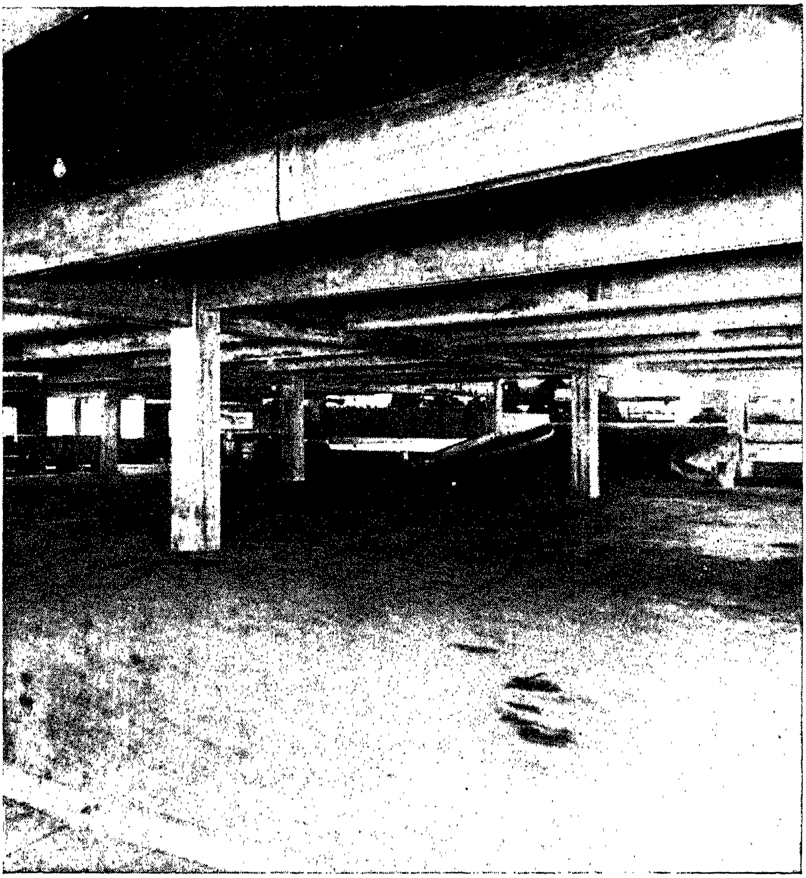


Fig. 3.—Corporation Bus Station at Blackpool built with Limestone Aggregate.

[*Facing p.* 22.

FLEXURAL STRENGTH OF CONCRETE

Importance of Flexural Strength. When requiring the strength of concrete [1] it has been customary to test cubes and cylinders in compression, and for many years the results have been considered a reliable indication of the quality of the concrete. Quite apart from the fact that strength is not necessarily the best measure for various types of concrete construction, resistance to compression may not be as important as resistance to bending, or possibly in some instances to tension. In certain types of work the flexural strength of concrete is of importance: for instance, numerous investigations connected with the design and construction of reinforced concrete road slabs have shown that the flexural strength of concrete must be considered, and since a concrete beam in flexure will break on the tension face, the matter is, to some extent, a question of tensile stress. Actually, however, the results obtained from tests on concrete in direct tension would not be the same as those obtained from concrete tested in bending, and to keep the distinction quite clear, the bending stress worked out by the customary formula is known as the "Modulus of Rupture".

In general, American highway engineers accepted the findings [2] resulting from the Bates experimental section in Illinois with regard to the design of the slab, for, since results from this project were published in 1924, almost all concrete pavements constructed in U.S.A. have had thickened edges. The basis for arriving at the proper edge thickness, using the accepted formula $d = \sqrt{\frac{3W}{S}}$, embodies the use of the flexural strength of the concrete. In the formula, S is the value representing not more than one-half the modulus of rupture of the concrete; so, for design purposes, engineers have generally accepted the value of 300 to 350 lb. for S, assuming thereby a concrete of 600 to 700 lb. per square inch modulus of rupture. W is the wheel load, and d is the depth of the slab.

Modulus of Rupture. In determining the modulus of rupture the usual assumptions are made for a beam subjected to bending

forces. The modulus is taken to be the tensile stress at fracture using the general formula given below.

Let f = modulus of rupture in lb. per square inch.
b = breadth of beam in inches.
d = depth of beam in inches.
I = moment of inertia of cross-section of beam in inch units.
y = distance of extreme fibre from neutral axis in inches.
M = maximum bending moment in inch-lb.

Using the basic formula $\frac{f}{y} = \frac{M}{I}$

we have $$f = \frac{My}{I}$$

and for a rectangular section this becomes

$$f = \frac{Md}{2} \frac{12}{bd^3} = \frac{6M}{bd^2}$$

Simple formulæ may be obtained for the three most common cases:

1. Cantilever.
2. Beam with centre loading.
3. Beam with third-point loading.

Compression and Flexure. As long ago as 1922, Abrams [3] pointed out that the relation between modulus of rupture and compressive strength is not uniform. A series of concretes having a certain classification when tested in compression will, in general, have a different classification when tested in flexure. This means that, though the rules for making good concrete will apply in a general way, various details will have to be modified, if the aim is to get a concrete which has a high flexural resistance rather than a high compressive resistance. Another inference to be drawn from this is that an aggregate which gives a concrete having high compressive strength does not necessarily impart high flexural strength as well.

Some New Jersey tests conducted in 1926 and reported in 1928 [4] show that there was as much as 12 per cent. higher flexural strength in concrete containing one coarse aggregate than in concrete containing another type of coarse aggregate, whereas there was practically no difference in the crushing strengths of these two concretes.

Nature of Aggregate. Many useful results have been obtained from flexural tests, but perhaps there is none quite so interesting as those dealing with the nature of the aggregate. Kellermann [5] found that, in general, aggregates having rounded fragments produce

concrete of lower flexural strength than aggregates which are composed wholly or in part of crushed fragments. He also found that there is a fairly well-defined relation between certain mineralogical characteristics of the coarse aggregate and the strength of concrete, calcareous aggregates in general giving consistently higher flexural and tensile strengths than siliceous aggregates.

These are rather sweeping statements, and later investigations may show that some modifications are necessary. In the meantime, the good results obtained with limestone as the coarse aggregate cannot be ignored.

Comparison of Aggregates. To gain some further information [6] on local materials, the Minnesota Highway Department made some transverse and compressive tests using the following five distinct types of coarse aggregate:

1. A smooth water-worn gravel largely composed of igneous rocks. All flat, elongated, and broken pieces were picked out by hand.
2. An ordinary commercial gravel containing crushed oversize.
3. A crushed limestone.
4. A crushed trap rock.
5. A crushed sandstone.

Using the same volumetric proportions (1 : 2 : 4) measured by weight, and making cement, sand, grading, water (with allowance for one-half hour's absorption), and curing the same for all specimens, nine 6-in. by 12-in. compression cylinders and nine 6-in. by 6-in. by 30-in. beams were made for each kind of coarse aggregate. With the same water-cement ratio the slumps for the various aggregates were as follows:

No.	Aggregate	Slump in Inches
1.	Smooth gravel	$6\frac{5}{8}$
2.	Commercial gravel	$4\frac{3}{4}$
3.	Limestone	4
4.	Trap	$2\frac{1}{4}$
5.	Sandstone	$4\frac{5}{8}$

The results of compression and transverse tests are shown in fig. 4. The slump test indicates that the smooth gravel could be used with less water: this should result in higher unit strengths.

Tests of Flags. In 1938 tests were carried out by Mr. R. H. Harry Stanger, Assoc.M.Inst.C.E., on several flags made with limestone as the aggregate. Four different gradings were used (from two different parts of England) and both 2-in. and $2\frac{1}{2}$-in. flags were tested, so that there were eight sets of results. The trans-

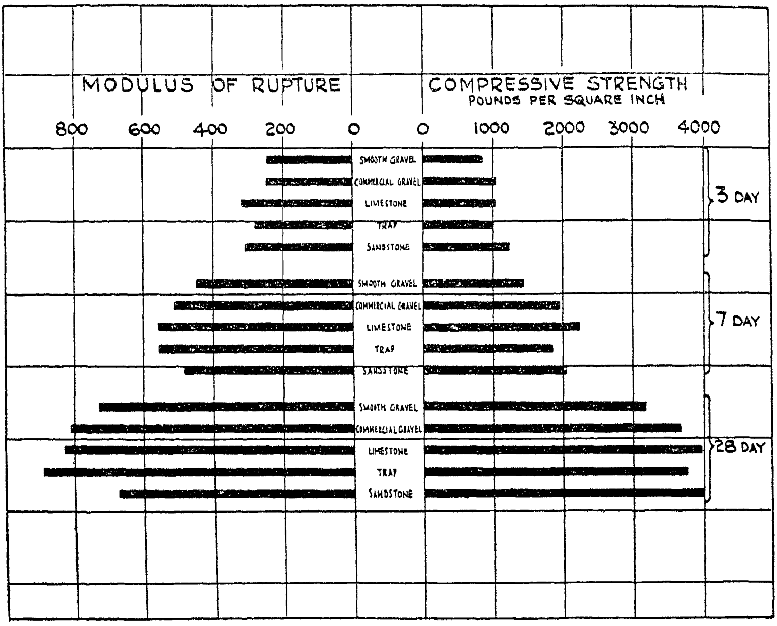


Fig. 4.—Strength of Concrete in Flexure and Compression. Relation between Aggregates at Different Ages.

verse tests are of interest as far as this chapter is concerned, and the results are given below:

Reference	Thickness in inches	Breaking load in lb. Average of 4 Flags	Breaking load in lb. B.S.S. No. 368—1936
DU	2	1,830	1,232
DU	2½	2,595	1,904
DW	2	1,980	1,232
DW	2½	2,848	1,904
VU	2	1,748	1,232
VUA	2½	2,102	1,904
VW	2	1,800	1,232
VW	2½	2,685	1,904

It will be seen that the flags comply easily with the B.S.S. requirements. In a letter sent on 18 October 1938, Mr. Stanger said that, in his opinion, the results of the tests on these slabs compared very favourably with the general run of paving slabs submitted for test.

Tests on Beams. Believing that concrete made with the English limestones would prove quite as satisfactory as that made with the American limestones when tested in flexure, some comparative tests were made by Mr. Stanger, at the request of the British

Limestone (Roadstone) Federation. The results were reported on 23 June, 1939, and a summary is given below.

To reduce the number of variables as far as possible, the proportions, sand, cement, age of beams, width of beams, depth of beams and span of beams were all standardised. The variable was the coarse aggregate, and this caused a slight variation in the water-cement ratio because it was arranged to keep the slump not less than 1 in. and not more than 2 in. As far as could be ascertained, the aggregates were good, representative samples of their respective types, and were obtained in the open market.

Proportions	4 : 2 : 1
Sand	Stone Court
Cement	R. H. Portland
Age of beams	28 days
Width of beams	4 in.
Depth of beams	6 in.
Span of beams	27 in.
Coarse aggregate	$\frac{3}{4}$–$\frac{3}{16}$ in.

Coarse Aggregate	Water-cement Ratio	Slump in.	Breaking Load lb.	Modulus of Rupture lb. per sq. in.
Carboniferous limestone	0·59	$1\frac{1}{2}$	3,670 3,740 3,340	680 700 630 Average 670
Granite	0·67	$1\frac{1}{4}$	3,050 3,050 2,460	570 560 450 Average 527
Uncrushed shingle	0·54	2	2,550 2,280 2,800	460 400 500 Average 453
Crushed shingle	0·57	2	3,470 3,200 3,270	610 550 570 Average 577

Comment. It is more than interesting to note that in all these tests limestone aggregate has proved singularly suitable.

Lang's tests, for instance, show clearly the satisfactory results obtained with limestone, both in flexure and compression. Tests on 6-in. cubes would, of course, give higher results throughout for the compressive strengths—a point which should not be overlooked when comparing American with English results.

CHAPTER VI

WATERTIGHT CONCRETE

To prevent the passage of water through concrete it is necessary to have both a watertight material and watertight construction. The concrete itself may be sufficiently impermeable to prevent the passage of water through it, and yet there may be leakage at joints or cracks. Far too often this point is not appreciated.

Permeability. When dealing with [1] the integral methods of waterproofing, it should be realised at the outset that the problem is one of reducing permeability, rather than entirely preventing the entry of water into, or passage of water through, the concrete. It is essentially a question of degree, since a slab of concrete which might be quite watertight under very low pressures would show leakage under high pressure. It [2] is not so much a matter of confining the water to its proper channels, as very few concretes carefully made and cured will show serious loss of water through percolation. The real need for watertightness is to prevent the disintegration caused by the freezing of saturated porous concrete or by the slow breaking down through solution of essential ingredients.

Glanville has stated that permeability [3] may be defined as that property which permits the passage of a liquid through a material and is thus distinct from the penetration of moisture into a substance by means of absorption due to capillary action. Until the liquid has penetrated through the material the rate of flow results from a combined pressure and capillary action, but when penetration is complete capillary attraction ceases and the rate of flow depends only on pressure. This rate of flow is a measure of the permeability of the material. Permeability must, therefore, be due to the existence of continuous passages right through the substance, and, in order to examine the causes of permeability, it is necessary to examine the nature and formation of these passages.

The first point, which is of fundamental importance in the study of this subject, is that, for any given concrete, permeability is a continually varying property, since it is intimately connected with the condition of the cement. For any particular combination of materials the more complete the hydration has been, the less permeable the concrete becomes. For this reason in most cases

the curing conditions and the period of subjection to water pressure outweigh other considerations.

Significance of Permeability Test.[4] A theoretical consideration of the factors involved would indicate that the permeability test should give a most reliable indication of the probable durability of concrete of a given design. An examination of existing structures and data from tests is, however, not so convincing. Most of the evidence of lack of adequate watertightness in structures seems to indicate that the distress shown has been largely due to segregation in handling and placing of the concrete rather than to a fundamental defect in the mix. Tests of any properly cured concrete which was so designed that a plastic workable mix was secured, show but very little permeability even under relatively high pressure. The moulding of small specimens of concrete for the test requires very careful technique or the results will be far from concordant. The problem of designing watertight concrete is not so much a problem in the design of a proper mixture as it is one of so handling and placing the material, while in a plastic state, that segregation of materials does not occur. The sequence of placing successive layers or portions of the work must be so adjusted that leakage does not occur at flow planes or construction joints. The fact that a permeability test indicated a certain mix would be watertight would be no assurance that the other conditions for watertight construction would be met.

Ordinary Constituents. It has been shown [5] repeatedly that concrete can be made sufficiently waterproof, under a 40-ft. head of water, for most practical purposes, without the addition of special materials. In permeability tests on such concrete it may be found that there is a slight flow of water into the specimen, so that, strictly speaking, the concrete would not be absolutely watertight, but the flow will be so small that no leakage will be apparent at the free surface. Such a concrete can be considered watertight for most ordinary purposes.

McMillan and Lyse have given us a very simple way of regarding the study of watertightness of concrete. They suggest that concrete should be thought of [6] as an aggregate mass thoroughly incorporated in a cement-water paste. If the aggregate particles are impervious, obviously any water which finds its way through the mass must pass either through the cement paste or through openings due to incomplete filling of the space with paste. Under this simple conception of concrete it can be seen that there are, in effect, only three requirements for watertightness, namely, (1) impermeable

aggregates, (2) a cement-water paste which, when hardened, will be impermeable, and (3) a mixture such that the paste completely fills the spaces between the aggregate particles.

So far as the permeability of the aggregate is concerned, the problem of producing watertight concrete need not be difficult. Limestone supplied by the members of the Federation will be found completely satisfactory.

The other requirements of watertightness, (2) and (3) above, which may be referred to briefly as the quality and distribution of the paste, involve all those factors which constitute the science and art of concrete making and placing. The quality of the paste has been found to depend on three factors: (*a*) the characteristics of the cement, (*b*) the proportions of the cement and water used, and (*c*) the extent to which the chemical reaction between the water and cement has been allowed to progress. Similarly, the distribution of the paste in a mixture depends upon the amount and consistency of the paste, upon the size, grading, proportions and other characteristics of the aggregate, and upon the method of placing. These are not independent variables, but are various means through which the quality and distribution of the paste can be controlled.

Percolation Test. In 1936 a percolation test was made on concrete in which the coarse aggregate was limestone. Details taken from R. H. Harry Stanger's report are given below. This test shows conclusively that limestone concrete is satisfactory as far as permeability is concerned.

Composition: 4 cub. ft. limestone chippings $\frac{3}{4}$–$\frac{3}{16}$ in.
2 cub. ft. Ham River sand.
90 lb. Portland cement.
Gauged with $7\frac{1}{2}$ per cent. water.

Dimensions of Specimen: 5 in. diameter (approx.) by 2 in. thick.
Area under Test: 20 sq. in. *Age at time of Test:* 14 days.
Storage Conditions: Kept in damp cupboard until due for testing.

Pressure			Quantity of Water percolating through Specimen per Hour
Per Square Inch lb.	Feet Head	Pressure maintained for	
20	46	One hour at pressure.	Nil
30	69		Nil
40	92		Nil
50	115		Nil
75	172		Nil
100	230		Nil
125	287		Nil
150	345		Nil

The pressure of 150 lb. per square inch was maintained for 18 hours, and the total percolation during that time was 3 c.c.

Rules for Watertight Concrete. The following simple rules may be given for making watertight concrete:

1. Use a cement of good quality.
2. Use clean, sound, well-graded aggregates (non-porous or of low porosity).
3. Use a fairly rich mix, such as 1 : 1½ : 3. In many instances, however, good 1 : 2 : 4 concrete will suffice.
4. Use the minimum amount of mixing water to give a workable concrete which can be puddled into place rather than tamped.
5. Mix the concrete for at least 60 seconds after all the materials are in the mixer. A longer mixing period will do no harm, and probably will be an advantage.
6. Place the concrete in approximately horizontal layers not more than 12 in. deep, and spade it well against the forms. Avoid honeycombing.
7. Avoid construction joints. If this is not possible, remove all laitance and take the necessary precautions to get a good bond.
8. Cure the concrete correctly by keeping in a warm, moist condition.

Cracks. Leakage in a concrete structure may be due to cracks. If there is to be no surface treatment the concrete must be free from cracks, and this presupposes, among other things, sound design. This crackless condition is also necessary for many of the surface treatments, as only an elastic covering can keep out water after concrete has cracked. On long structures cracks are unavoidable unless construction joints are placed at suitable intervals. This is a question of design, but is mentioned to show the importance of considering all the factors involved when dealing with a waterproofing problem. There may be (and very often is) leakage at construction joints due to the formation of laitance and the unsatisfactory bonding of the new to the old concrete.

As cracks depend partly on the shrinkage of the concrete, it would seem that aggregates giving low shrinkage values would produce concrete having less tendency to crack. This is a point which has not yet been given much attention.

Concrete cracks because internal stresses are set up which are too great for the material to resist. These stresses are produced by:

1. Changes in moisture content.
2. Changes in temperature.
3. Loading.
4. Chemical reaction.

Moisture. The expansion and contraction of concrete and

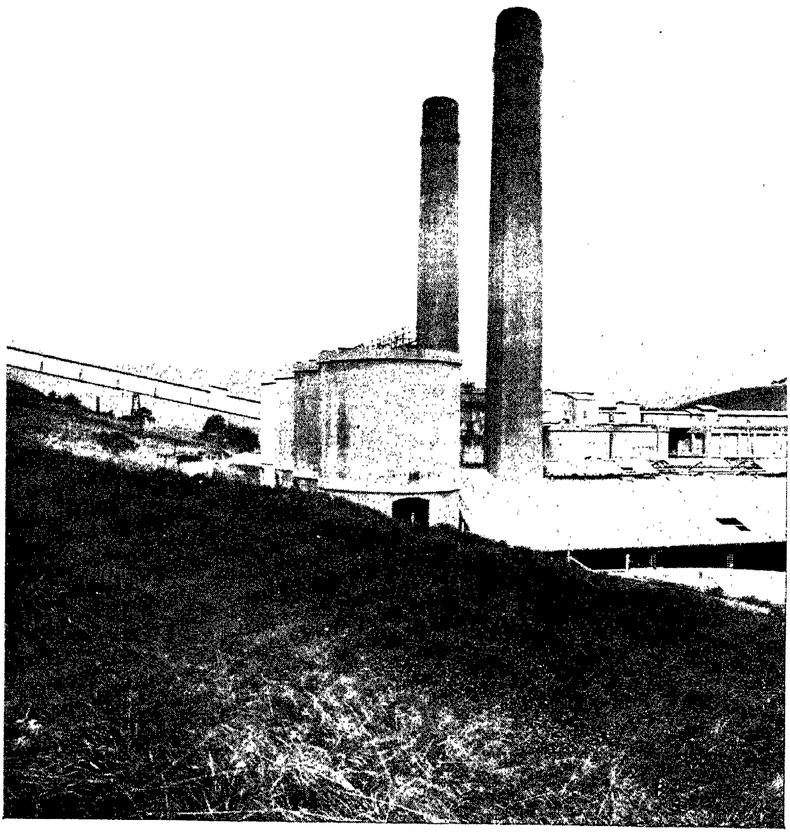


Fig. 5.—Slurry Tanks and Chimneys at Hope built with Limestone Aggregate.

[*Facing p.* 32.

mortar due to moisture changes cannot be ignored. The fact that shrinkage is bound to occur in a specimen which is drying out and which is free to move, indicates that a tensile stress will be set up in a specimen which is restrained. When this stress passes a certain point the concrete cracks. This is inevitable. Good designers of concrete and reinforced concrete structures allow for these forces.

Upon changing [7] from the dry to a completely saturated state, or vice versa, the change in length of an average concrete is of the order of 0·00055 per unit, or approximately that which would be caused by a change in temperature of 100 deg. F. The effect of continuously maintaining within concrete a moisture content sufficient to permit hydration of the cement is in general to produce expansion over an extended period of time, the amount of this expansion in average concrete ranging from about 0·0001 to 0·0002 per unit of length at ages upwards of three months.

Expansion and contraction of concrete during wet and dry storage are influenced greatly by variations in the type of mineral aggregate. Sandstone, trap and gravel concretes may be expected to undergo volume changes 50 to 100 per cent. greater than limestone or quartz concrete subjected to the same conditions. However, a given aggregate which produces high expansion in concrete during wet storage may not produce high contraction in dry storage, and vice versa.

Temperature. Much of the cracking which occurs as the result of temperature variations can be reduced by the use of distribution steel. It must be realised that some temperature cracks are inevitable, but by careful design they can often be located in predetermined positions. Temperature and moisture may give a cumulative effect, or they may counteract each other.

The thermal coefficient of expansion [8] of concrete varies with the character of the aggregate, ranging in one series of tests on 1 : 4½ concrete from 0·0000038 to 0·0000066 per degree Fahrenheit, the lowest coefficient being for concrete containing limestone.

Comment. These notes demonstrate that:—

1. Curing conditions are more important than variations in the aggregate, as far as permeability is concerned.
2. Leakage may occur at joints or cracks, even when the concrete itself is impermeable.
3. The risk of cracks can be reduced by the use of limestone aggregate.
4. Limestone concrete is eminently suitable for the construction of watertight structures.

CONCRETE AND FIRE-RESISTANCE

Introduction. In 1922–23–24 the writer [1] had a series of articles on "Reinforced Concrete and Fire-Resistance" [2] published in *Concrete and Constructional Engineering*, and these in turn were based on a paper [3] he read in February 1922 before the Manchester and District Association of the Institution of Civil Engineers. More recently a summary was given in his paper, "Limestone as an Aggregate for Concrete", read in 1932.[4] For full details reference should be made to these articles, but the following points summarise the matter satisfactorily for our present purpose.

At the outset it is essential to appreciate the fact that there is no such thing as a "fireproof" building. "Fire-resisting" is the correct term to use, and this obviously is a question of degree.

Extensive experiments carried out in the United States and in this country have shown conclusively that of the natural aggregates limestone is the most suitable for concrete for fire-resisting purposes.

Reinforcement. Before dealing with the fire-resisting properties of concrete, brief reference must be made to the effect of increased temperatures on the strength of steel, as this has an important bearing on reinforced concrete work.

Reinforced concrete will be sure to fail on exposure to fire whenever the steel reaches such a temperature [5] that its yield point is less than the stress to which it is subjected when the beams and slabs are carrying loads for which they are designed. That is, if the reinforced concrete beams and slabs of a building are designed to have a working stress in the steel of, say, 7 tons per square inch, then if during a fire the steel could by any means reach a temperature at which the yield point was less than this, the floors would be bound to collapse.

Fig. 6 shows the results obtained by Lea from mild steel which had been supplied for reinforced concrete. The curves show clearly what happens, and several points are worthy of note:

Breaking strength at 0° C., 30 tons per square inch.

Maximum strength occurs at about 235° C.

Maximum strength, 43 tons per square inch.

Beyond 300° C. the strength diminishes very rapidly, and at a

temperature of 615° to 640° C. the breaking strength becomes less than 7 tons per square inch. The actual temperature (within narrow limits) at which fracture takes place at this stress (7 tons per square inch) depends upon a time factor of heating and loading.

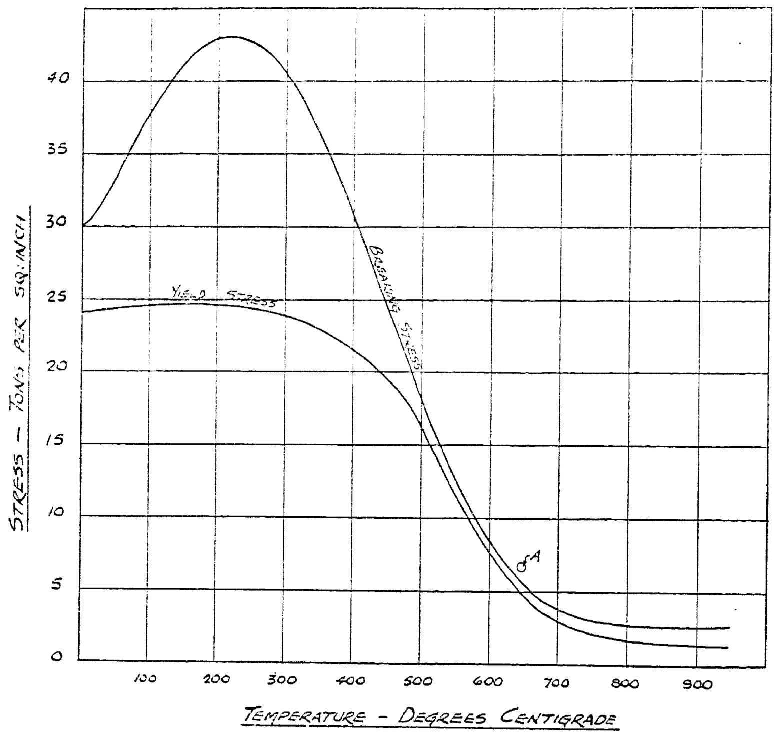


Fig. 6.—Effect of Temperature on Strength of Mild Steel.

For instance, points lying on the curves were obtained by bringing the specimen to a steady temperature, maintaining it at this temperature for 20 minutes and then breaking. On the other hand, two coinciding points at " A " were obtained by loading bars with a stress of 15,900 lb. (7·1 tons) per square inch and gradually raising the temperature of the specimens until they broke. It will be noticed that the points " A " lie very close to the curves.

It may be pointed out, however, that the yield stress is the one which should be used when considering the factor of safety, and that the danger point will be reached when the yield stress, and not the breaking stress, reaches 7 tons per square inch. It is interesting to note, therefore, that at the dangerous temperature (600° to 650° C.) the curves of breaking stress and yield stress

practically coincide, implying that fracture occurs immediately after yielding. For all practical purposes, then, in the question of fire-resistance, we can take it that both the yield stress and the breaking stress reach the value of 7 tons per square inch at a temperature of 600° to 650° C.

B.F.P.C. Tests. Tests on concrete slabs made with various aggregates bought in the open market have been reported in various "Red Books" published by H.M. Stationery Office. A summary of the results has been given by D. W. Wood.[6] This (as far as natural aggregates are concerned) is given briefly below.

Plain Concrete Slabs. Thames ballast, or any flint aggregate, proved unsatisfactory from a fire-resistance standpoint. Gravels and sandstones were also unsatisfactory. Limestones showed somewhat better results. Igneous rocks were generally poor, Nottingham basalt proving the best, with trachyte next. Granites did not behave well.

Reinforced Concrete Slabs. The different aggregates gave similar results to those in the case of plain concrete.

Conductivity Tests. Parallel with the tests of plain[7] and reinforced concrete slabs the heat conductivity of the various concretes was measured. In 22 out of 30 tests the temperature at 1 in. from the soffit was 1,200° F. or higher at 4 hours. The coarse aggregates in the slabs which did not attain to 1,200° F. were slag, limestone (2), basalt, andesite, coke breeze (sand as fine aggregate), broken brick and dolerite (whinstone). The highest temperatures at points near the top of the slabs were attained with concretes having as coarse aggregates siliceous gravel (2), calcareous gravel, coke breeze (fine coke breeze as fine aggregate) and quartzite.

Pittsburgh Tests. The following is an extract from the summary of the results of fire tests on concrete and reinforced concrete columns made at the Pittsburgh laboratories of the Bureau of Standards by W. A. Hull and reported by him in the *Proceedings of the American Concrete Institute.* The investigation[8] was designed to secure information as to the effects of the kind of aggregate, the type of reinforcement and the shape of the cross-section, on the fire resistance and the strength of the columns at high temperatures.

The tests gave widely different results, due mainly to the differences in the mineral composition of the aggregates. Aggregates with high quartz, chert or granite content were found likely to induce spalling or serious cracking of the concrete when subjected to fire of moderate intensity and duration. On the other hand, concretes made with calcareous aggregates, such as limestone or

CONDUCTIVITY TESTS BY BRITISH FIRE PREVENTION COMMITTEE

Coarse Aggregate	Fine Aggregate	Mix	Order of Merit for 1-in. Protection *	Order of Merit for 2-in. Protection †
Limestone	Sand	1 : 2 : 4	100	100
Whinstone trap rock	Sand	1 : 2 : 4	89	95
Basalt	Sand	1 : 2 : 4	84	99
Sandstone	Sand	1 : 2 : 4	83	96
Granite	Sand	1 : 2 : 4	69	90
Irish pit pebble	Sand	1 : 2 : 4	67	66
Gravel	Sand	1 : 2 : 4	66	87
Pan breeze	Fine pan breeze	1 : 2 : 4	91	88
Burnt gault clay	Sand	1 : 2 : 4	88	121
Slag	Sand	1 : 2 : 4	81	81
None	Fine coke breeze	1 : 5	78	108
Brick	Sand	1 : 2 : 4	73	96
Coke breeze	Sand	1 : 2 : 4	72	82
Clinker	Sand	1 : 2 : 4	61	86
Coke breeze	Fine coke breeze	1 : 2 : 4	29	53

* Based on the time required for concrete to attain 1,000° F. at 1 in. from the soffit of the slab.

† Based on the relative temperatures attained at the end of 4 hours.

In each case limestone concrete is considered as 100 (arbitrary point on the scale).

calcareous gravel, suffered few visible effects even when exposed to very severe fires of four hours' duration. Concretes made with trap rock or blast-furnace slag gave results intermediate between these.

The poor showing of the concrete columns made with siliceous aggregates when subjected to fire is due mainly to the expansion characteristic of quartz and other forms of silica and minerals containing them. They spalled and cracked very badly, exposing the reinforcement in most cases to the high temperatures of the surface. Increasing the thickness of the covering to $2\frac{1}{2}$ in. did not give suitable protection. Columns made with concrete having limestone or calcareous gravel aggregates gave quite the best showing of all columns having concrete protection. They did not crack or spall extensively, nor did the dehydration of the concrete reach to as great a depth. The limestone near the surface was calcined. Concretes made with these aggregates had better heat-insulating qualities than the others.

Chicago Tests. The table [9] shows in simple form comparison

between various aggregates. It is clear that limestone is easily the best.

TESTS AT THE CHICAGO UNDERWRITERS' LABORATORIES
Fire-resistance Periods Derived from the Test Results

Type of Column	Protection Material	Nominal Thickness of Protection. Inches	Fire Resistance Period. Hours
Structural steel . .	Concrete: siliceous gravel aggregate	2	1
" " . .	Ditto	4	$2\frac{1}{2}$
" " . .	Concrete: granite, sandstone or hard coal cinder aggregate	2	$2\frac{1}{2}$
" " . .	Ditto	3	$3\frac{1}{2}$
" " . .	Ditto	4	5
" " . .	Concrete: trap rock aggregate	2	3
" " . .	Ditto	3	4
" " . .	Ditto	4	5
" " . .	Concrete: limestone or calcareous gravel aggregate	2	4
" " . .	Ditto	3	6
" " . .	Ditto	4	8
Round cast iron .	Concrete: trap rock, granite or hard coal cinder aggregate	2	2
Reinforced concrete	Limestone or calcareous gravel concrete	2	8
" "	Trap rock concrete	2	5

Mineral Composition. Fire and fire tests [10] have shown a marked difference in effect on concrete made with different kinds of aggregates, which has been shown to be caused by differences in mineral composition of the aggregates involved. Four general groups are recognisable: (1) calcareous, (2) feldspathic, (3) granites and sandstones, and (4) siliceous aggregates.

The mineral composition of the coarse aggregate has a greater influence on the fire-resisting properties than that of the fine aggregate, due to the greater amount entering into the mix and possibly also to the coarser gradation.

Decarbonation. Discussing the results of fire tests on concrete columns, W. A. Hull suggests it should be taken into consideration [11] that there is some advantage, thermally, in the decarbonation of the limestone next to the surface of the column. High calcium

limestone decarbonates rapidly, under these conditions, at temperatures approximating 900° C. The reaction is endothermic, the decarbonation of a pound of limestone absorbing approximately the same amount of heat as the evaporation of three-quarters of a pound of water. Heat penetrates concrete with some difficulty and the absorption of heat in the course of its passage through an insulating material may become an important factor in retarding temperature progress in the protected member. This is pretty generally appreciated in connection with the thermal effect of the driving off of water, as in the dehydration of gypsum, but has not been so generally taken into consideration in connection with the driving off of carbon dioxide. Inasmuch as the quantity of limestone in the layer, of a thickness of $\frac{5}{8}$ to $\frac{3}{4}$ in., which was decarbonated in these tests, was considerable, the thermal effect of the heat absorption should not be wholly disregarded. Furthermore, it is probable that because of its greater porosity, the decarbonated material would be a somewhat better heat insulator than the original limestone, so that, from the thermal standpoint at least, decarbonation of limestone may be considered as an advantage. As to compensating disadvantages of the decarbonation, this action is hardly to be charged with any weakening of the column, for any concrete which had attained a temperature of 900° C. could no longer be counted on for any considerable strength. As to the matter of repair after a fire, the slaking off of the outer concrete to a depth of, say, $\frac{3}{4}$ in. might entail some expense in replacement, provided the concrete did not have to be replaced to a greater depth than this, irrespective of the calcination. But there may be some compensation for this in the fact that the depth to which the decarbonation of the limestone has progressed can serve, at least roughly, as an index to the severity of a fire and the probable condition of the inner concrete; this is at least a better index than judgment based on the depth to which the concrete appears to be dehydrated when attacked with a pocket-knife.

Summary. It is not suggested that limestone concrete may not require repair after a fire, but it is believed that owing to the high fire-resistance period, a building in which limestone aggregate is used is likely to be safe for a much longer period than when many other aggregates are used. The following extract gives in a brief form the opinion of an American expert on calcareous aggregates used in fire tests :—

The group[12] giving the least disruptive effects and the lowest temperature transmission includes calcite and dolomite as contained in high-calcium

and calcium-magnesium limestones, sand and pebbles. The temperature travel within the material from fire exposure is retarded by the calcination of the limestone which involves a change from the carbonate to the oxide requiring some 430 calories per gram for calcium carbonate and 340 calories per gram for magnesium carbonate. The calcined material itself possesses good heat-insulating properties. The melting points of the oxides formed are considerably higher than temperatures occurring in building fires even with the impurities ordinarily present, hence effects from fusion should not be expected. After the fire, on exposure to air for a few weeks the oxides hydrate or "air-slake", and fall off, and hence surfaces of concrete made with calcareous aggregates will require repair after fire exposures of any considerable severity.

In numerous tests limestone has been shown to be superior to other natural aggregates in its fire-resisting qualities. There is little or no tendency for the limestone concrete to spall or crack and its insulating value is generally greater. In fires of long duration the limestone aggregate near the surface becomes calcined, and in some cases necessitates more surface repair to the protective covering, but this is a minor point when compared with the question of safety during the fire.

There seems to be an impression in some quarters that, because lime is made by burning limestone, a limestone aggregate will crumble and disintegrate almost at the beginning of a small fire. Anyone who thinks like this is losing all sense of proportion. It was with this point in mind that a simple test was made, and an extract from Stanger's report (2 July, 1936) is given below:

A sample of the limestone was heated for two hours at 500° C. At the end of this period it was found to be virtually unaffected, and the recorded loss in weight was negligible. It was then returned to the furnace and heated for a further six hours at 600° C. The sample was still hard and strong. It had lost 0·5 per cent. in weight, probably carbonaceous matter.

In view of these results I consider the material to be suitable for use in concrete designed for high temperature resistance up to a temperature of 600° C. In this case I am assuming that the maximum temperature is only reached occasionally and for short periods, as continuous heating at 600° C. would probably reduce the strength of the aggregate considerably, but as this would also apply to the matrix, the circumstance is hardly likely to arise in practice.

CHAPTER VIII

DURABILITY

WHEN he makes concrete, an engineer's first requirement usually is strength, but he also wants durability. In its widest sense, durability refers to the resistance of the concrete to all types of destructive influences, such as weathering, abrasion, chemical attack and fire. In some quarters there has been a feeling that as limestone has (considered broadly) the same chemical composition as one of the constituents of Portland cement, it will react chemically with the cement when mixed with it in the concrete. This is a fallacy. It would be no exaggeration to say that the writer has heard this point used scores of times as an argument against the use of limestone. The best way to counter this notion is to consider the large number of structures throughout the country in which limestone has been used as an aggregate. Assuming that the concrete has been made and placed in accordance with good practice, it will remain perfectly sound.

The durability of limestone concrete is most satisfactory, and evidence can be produced to convince the most sceptical that there is no risk at all in using limestone on account of its chemical composition. Structures of all types can be found to show that concrete made with limestone is quite as durable as concrete made with other aggregates, provided the usual precautions are taken in connection with grading, mixing, placing, curing, etc. In other words, with good concrete practice a limestone aggregate will produce first-class and durable concrete.

Volume Change. Durability, or resistance to the action of weather, is a property difficult to evaluate, but it seems reasonable to assume that, other things being equal, the concrete having the least volume change will generally be most durable [1] since it is least subject to internal stresses and possible cracking. Volume changes accompanying variations in temperature and moisture induce local or internal stresses by themselves in any unrestrained member and may also cause other stresses in a restrained member or in connecting members, due to such restraint. In this respect, limestone has an advantage, as was shown in Chapter VI.

WEATHERING

Natural weathering includes [2] freezing and thawing of entrained moisture; solution action of normal water; action of alkaline or acid waters or sea water; internal stress due to variations in water content of various parts of the mass, and resulting volume change; internal stress due to variations in volume change of component parts due to temperature change; internal stress due to failure on the part of the designer to make adequate provision for volume change in the structure as a whole; and internal stress due to intercrystalline growth.

One of the most obvious actions is the solution effect of water. When cement hydrates,[3] lime is liberated and is free to join with carbon dioxide, forming calcium carbonate. Lime is soluble in pure water, and calcium carbonate is soluble in water containing carbon dioxide, so that they are liable to be drawn from the concrete if it is porous and exposed to moisture. This weathering effect should not be regarded too seriously, as it happens with all building materials, and it would appear that normally well-made concrete will last at least as long as any competitive building material exposed to the same conditions.

Frost. In 1932 tests were reported in connection with the resistance of concrete to frost.[4] The most interesting fact to be noted from a study of the results is that, in spite of the wide variation in the quality of the coarse aggregate used, failure of the concrete on freezing and thawing in practically all instances was due to a weakening and consequent breaking down of the mortar portion of the concrete. Although some of the coarse aggregates were composed either of very soft or friable pieces, or showed unsoundness by the sodium sulphate test, the concretes in which these materials were used were, in general, just as frost-resistant as concrete containing coarse aggregate of known durability. This applied to both the 1 : 2 : 4 and the 1 : 1½ : 3 mixtures, although a study of the data shows in almost all cases greater resistance in the 1 : 1½ : 3 mixes. This is due, no doubt, to the fact that in the richer mixtures the aggregates were incorporated in a paste having a considerably lower water-cement ratio, with consequently increased resistance to frost action.

It should be appreciated that these tests were not extensive enough to warrant drawing definite conclusions. It is believed, however, that certain trends have been indicated with sufficient

definiteness to throw some additional light on this particular problem. These indications are as follows:

1. That, within the range in variation of aggregate quality covered by the tests, variations in the quality of mortar caused by changes in the water-cement ratio of the cement paste will have a greater effect upon the resistance of concrete to frost action than will variations in the type and character of the coarse aggregate.
2. That failure of coarse aggregates in the sodium sulphate soundness test is not necessarily an indication that the aggregate is unsatisfactory for use in concrete to be exposed to the weather.

Young's Conclusions. In connection with the work of a committee of the American Concrete Institute dealing with "Durability of Concrete", Young read a paper in 1931 to give some of the results of examinations of concrete structures. Summing up, he arrived at the following conclusions.[5]

1. Generally speaking, concrete structures are satisfactorily performing the functions for which they were built.
2. While few concrete structures are wholly free from deterioration, the excellent condition of the greater part of even those which would be classed as examples of poor concrete, and the outstandingly good condition of others twenty or more years old, are proof that concrete is and can be made durable.
3. Most cases of deterioration can be classified into a few types to which definite causes can be assigned.
4. Most of the defective concrete is due to faults of workmanship, the use of excess water, and other causes that are strictly preventable by the exercise of reasonable care and supervision during construction.
5. Faulty construction joints are very prevalent and under certain circumstances may start dangerous deterioration.
6. Unsound aggregate can cause serious disintegration, but trouble of this kind is not general and usually does not become a factor in destroying concrete unless the concrete is otherwise unsatisfactory.
7. Cement is seldom a primary cause of concrete deterioration.
8. The principal naturally occurring destructive agents affecting concrete are frost, water, and the corrosion of embedded steel.
9. Water, if allowed to penetrate concrete may, and often does,

totally destroy it due to its solvent action on the cementitious binder.

10. Fundamentally, most concrete deterioration is due to its being porous.
11. The best recipe for durable concrete is to make it so dense and impermeable that water cannot enter.
12. Harsh, unworkable concretes are prone to deteriorate.
13. Lean concretes, no matter how strong, are not durable.
14. Intelligent and constant supervision of concrete during construction is necessary to ensure durable concrete.

Comment. It is clear from the above notes that when discussing the question of durability we must not lose our sense of proportion. The most important thing of all is to make concrete which is watertight—everywhere. Given watertight concrete—i.e., concrete which is, and which remains, watertight, at all points and under all normal conditions, there will not be much to fear. Further investigation of this problem, therefore, becomes a matter of considering watertight concrete.

In the meantime, we can leave the argument and investigate the durability of limestone concrete in existing structures.

EXTRACTS FROM ARTICLE BY GOLDBECK[6]

It seldom occurs that limestone or dolomite is the subject of any doubt when used in concrete exposed to water action. At times, however, this question has been raised, in all probability because of the known solubility of calcium carbonate or magnesium carbonate when subjected to acid solutions. It is a fact that both limestone and dolomite are soluble in water to some extent as attested by the presence of underground caves in limestone or dolomite areas.

The geologist looks upon limestone and dolomite as being among the more soluble mineral constituents of rocks, and from the geological standpoint and thinking in terms of geological ages, no doubt limestone and dolomite in a relative sense might be considered as non-durable materials. But before condemning such materials for use in concrete for engineering structures, it will be well to examine all the facts and not be governed merely by geological experience.

Solubility of Cement in Water. Perhaps the first thought which occurs to anyone in connection with the resistance of concrete to the action of water is, What is the relative solubility of

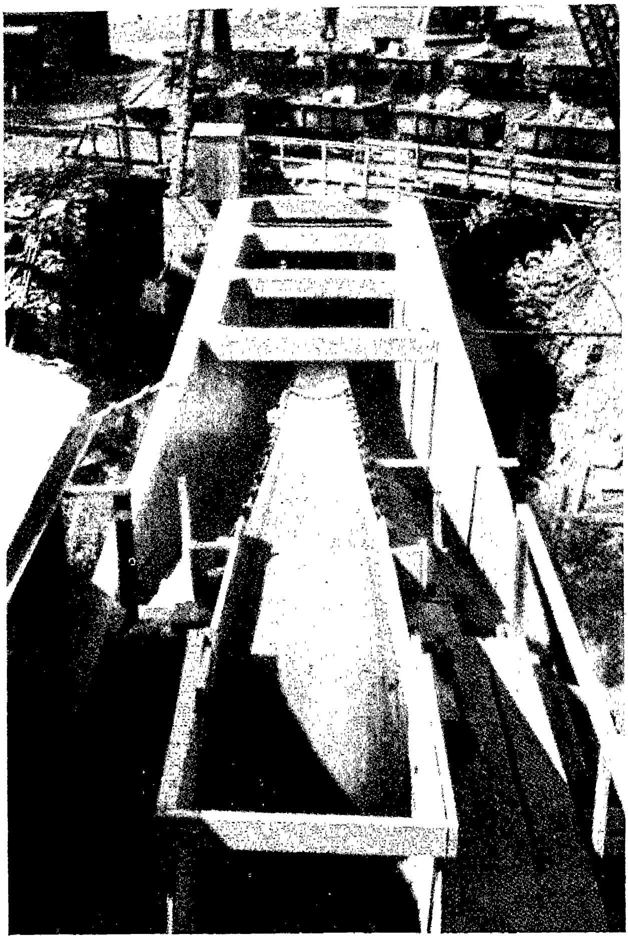


Fig. 7.—Concrete Pit, New York, built in 1924 with Limestone Fine and Coarse Aggregates. Subjected continuously to Water with no Deterioration and no Leakage.

[*Facing p.* 44.

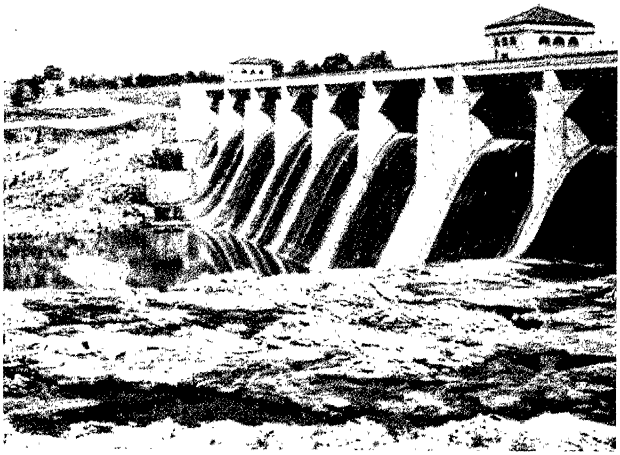


Fig. 8.—O'Shaughnessy Dam built in 1925 near Columbus, Ohio. Limestone Coarse Aggregate used. No signs of any Solution of the Stone.

Fig. 9.—Dam at New Braunfels, Texas, built in 1922 with Limestone Coarse Aggregate. Continuously under Water with no signs of Deterioration.

the various constituents? If the cementing medium dissolves, naturally the aggregate will no longer be bonded together. Evidence on the relative rate of solubility of Portland cement paste and limestone aggregate may be obtained from various sources in articles already published.

Laboratory evidence would seem to point to the fact that even though limestone and dolomite may be slightly soluble in water, the binding medium is unquestionably much more soluble in water, and this accounts for the service evidence obtained from a number of eminent sources to the effect that limestone or dolomite concrete subjected to water action does not fail due to any solvent action of the water on the aggregate, but rather that when such failure does take place the solution of the cementing medium is a primary factor.

Experience of Eminent Authorities. The writer has conducted correspondence with a number of the most important agencies having to do with the construction of hydraulic structures or with their investigation. In not one single instance has any of the eminent engineers reporting on this subject been able to point to a case where trouble with the concrete has been due to the solvent action of water on either limestone or dolomite coarse aggregate. It would seem therefore that this particular possibility of trouble from the use of limestone and dolomite can be dismissed from consideration in the light of laboratory investigations and also of long years of experience.

In the *Crushed Stone Journal* of June, 1931 there appears an article by Roderick B. Young, Testing Engineer of the Hydro-Electric Power Commission of Ontario. This article, entitled "More Lessons from Concrete Structures in Service", was originally presented as a paper before the twenty-seventh annual convention of the American Concrete Institute. Among other conclusions, Young gives the following:

> Unsound aggregate can cause serious disintegration, but trouble of this kind is not general and usually does not become a factor in destroying concrete unless the concrete is otherwise unsatisfactory.
>
> Water, if allowed to penetrate concrete, may and often does, totally destroy it due to its solvent action on the cementitious binder.

It will be noted that Young lays emphasis on the cementing medium rather than on the aggregate as being the cause of trouble if the concrete is of a porous nature. He gives no citation of trouble due to the solvent action of water on either limestone or dolomite.

Abrading Action. In certain types of hydraulic structures which carry flowing water containing abrasive material in suspension, the question comes up as to the relative wearing effect of these abrasive materials on the Portland cement mortar as compared with that on limestone. No direct test results seem to be readily available, but light is thrown on this question by tests performed in the U.S. Bureau of Public Roads and reported by F. H. Jackson in the *Journal of Agricultural Research*, 30 July, 1917. On page 269 of that journal are shown the results of hardness tests made by means of the Dorry hardness machine on Portland cement mortars. These results taken from Fig. 3 of that report are as follows :

Proportions by Volume	Loss in Grams (1,000 rev.)	Calculated Dorry Hardness Coefficient (20–1/3 Loss)
Neat cement	16	14·67
1 : 1	7·5	17·5
1 : 1½	6	18
1 : 2	5	18·3
1 : 3	5	18·3
1 : 4	12	16

The sand used was Potomac River sand and the specimens were stored for seven days in water.

A good grade of dolomite will have a Dorry hardness coefficient of about 17·5 and some limestones will run lower than this figure. It is evident, however, that the neat cement paste is the least resistant to abrasion of any of the constituents in the concrete, unless an extremely soft stone is used.

In the previously cited water tunnel which was examined after twenty-five years' service, trowel marks on the mortar were still visible, so that the scouring action was almost nil. Evidently, a very high velocity of current carrying sediment becomes necessary before scouring becomes an important factor in the life of the concrete, and this kind of failure of water-contact structures made of concrete is extremely rare.

Certain chemicals carried in solution such as sodium and magnesium sulphate, carbon dioxide and dilute acids will, of course, accentuate the destructive action of water. Their effect, however, is primarily on the cementing medium and to a very much less degree on the aggregate. Volumes of literature have been written on the action of sulphates on concrete, and this is a separate study.

Conclusion. In conclusion, there is one outstanding fact, namely, that limestone and dolomite aggregate do not cause trouble in concrete through their solution when in contact with water. The least resistant portion of the concrete seems to be the cementing medium, but in spite of this fact concrete structures are highly resistant to water action, provided care is taken to proportion, place and cure the concrete so as to obtain a dense, impermeable mass.

CORRESPONDENCE

In addition to the foregoing information on the durability of limestone, the writer has had correspondence with various engineers, and the following extracts from their replies will be of interest.

American Concrete Institute (3 *November*, 1937). While there is plenty of scattered evidence throughout the literature of the American Concrete Institute that limestone aggregate is pretty generally accepted for use in concrete work in this country, it seems that there is not available within the compass of a few papers and reports the information which you require.

Crushed Stone Association, U.S.A. (10 *November*, 1937). Limestone is universally used in this country for highway construction, that is, limestone concrete construction, and limestone concrete highways are notably free from cracking as compared with other aggregates.

No distinction is ever made in our national specifications regarding the use of limestone in concrete for any purpose, except possibly in connection with sewer work where limestone of extra high quality is usually specified, together with other aggregates.

Portland Cement Association, U.S.A. (21 *January*, 1938). In this country the use of limestone for crushed aggregate as an alternative to gravel is practically taken for granted. Thousands of structures and miles of concrete highways have been built with limestone as coarse aggregate.

Of course it is essential that the limestone be of good quality. Limestone containing cherty materials or considerable argillaceous material of high absorption would be objectionable.

I am attaching a reprint from *Engineering News-Record* discussing the conditions of the Tunkhannock Viaduct after 17 years' service. This indicates that where a good grade of limestone is used, and observing the basic principles of concrete-making, entirely satisfactory results can be secured.

Another project is Wacker Drive in Chicago, built about 14 years ago. This is a double-deck street along the river-front extending for a distance of three-quarters of a mile, and in which limestone was used throughout. The concrete is in excellent condition.

EXAMPLES OF STRUCTURES

Numerous examples could be given to show the extreme durability and suitability for all types of work of limestone concrete.

Three examples are given here, and for others reference should be made to the various illustrations in this book. Extensive information will be supplied on request by any member of the Federation.

Swimming-bath. The swimming-bath at Plymouth was constructed in concrete, and broken limestone was used for the aggregate. The work was done in the summer of 1935, and the proportions of materials used were generally 4 parts of limestone : 2 parts of sand : 1 part of cement. The work is completely satisfactory in every respect.

Water Tank. In 1929 limestone chippings were supplied for a reinforced concrete water tank which forms part of a coal-washing plant (in England). The proprietors have supplied the following information :

> We have often used a limestone aggregate for this type of work, and find that such concrete will remain waterproof and in good condition after many years. The mix used is the normal 1 : 2 : 4, with a slump of about 6 in. for the conical walls.

Viaduct. The following extracts are taken from an article [7] which appeared in the American journal, *Engineering News-Record.*

> A structure that has the distinction of being the most prominent or largest of its kind receives special and at the same time critical attention from engineers. The Tunkhannock Viaduct of the Lackawanna R.R. for many years has had this prominence. As the largest concrete railroad bridge in the world it has been subject to close scrutiny by railroad engineers both of this country and those visiting us from abroad.
>
> The recent inspection shewed that in general the structure's 165,000 cu. yd. of concrete is in perfect condition. Very few spots mar this perfect condition, and these are concentrated in two locations; both are clearly accounted for by faults of construction.
>
> The splendid condition of the Tunkhannock Viaduct after seventeen years of service under severe climatic exposure could not be simple accident of construction in a structure of this magnitude. The service has been sufficiently long to test the durability of the material as well as the adequacy of design and construction.
>
> A 1 : 2 : 4 mix was used for the floor system of the abutment spans and 1 : 3 : 5 mix for the remainder of the structure (with derrick stone in the piers below springing line to form cyclopean concrete). The coarse aggregate was sound, broken limestone from Syracuse; the sand was Hodgson sand from Netcong, N.J. A standard brand of Portland cement was used.

CHAPTER IX

EXPOSED AGGREGATE AS A SURFACE FINISH FOR CONCRETE

Introduction. This chapter is based on two of the writer's articles which were published in *The Master Builder*, and acknowledgment is made to the editor and publisher of that journal. The information is given here as it is felt that the use of limestone aggregate for this type of work has immense possibilities. Reference should be made to the articles for additional details.

There is a prejudice against concrete when architectural values are being considered, due to its colour and texture when made with ordinary grey cement, and untreated in any way. The finish normally obtained owes its characteristics to the cement, and it cannot be stated too strongly that cement is not concrete. We all know this, but many of us act as though we did not. If the average layman were to see the surface skin of grey concrete removed and the hidden beauties of the aggregate exposed he would be quite certain that he was not seeing the treatment of ordinary concrete at all. Comparatively few people realise the architectural value of the aggregate in concrete—and it is there whether it is used or not, even when the usual everyday constituents are employed.

Possible Treatments. There are so many methods of dealing with a concrete surface that a suitable logical classification which will include every possible treatment and meet with universal approval is difficult or impossible to obtain. However, it seems to the writer that there are three fundamental groups into which the treatments can be divided, i.e.:

1. Concrete as formed by sheeting or moulds.
2. Concrete with aggregate exposed.
3. Concrete with applied finish.

In the second group, which is our present concern, there are two divisions:

(*a*) Where the aggregate is unbroken.

(*b*) Where the aggregate is broken.

The Surface Skin. On the surface of normal concrete which has been correctly mixed and placed there will always be a skin

of cement and fine sand, sometimes referred to as the "fatty face", of a dull grey colour. Unfortunately, this "finish" is the one frequently associated with concrete, and is that visualised by many engineers and architects when concrete surfaces are considered. To remove this face and thus expose the hidden beauties of the aggregate is a simple matter, and at a slight cost the grey surface can be changed to one having almost any predetermined colour and texture.

To some people this is the most interesting method of treating concrete surfaces, and there seems little doubt that it will be used a great deal in the future. It has certainly passed the experimental stage, and there are many practical examples available for inspection. The principle of the method is to remove the film of cement in some suitable manner and thus reveal the particles of aggregate.

Whilst it is necessary to remove this surface skin to obtain certain artistic finishes, it is also advisable to remove it for other reasons. The skin, which is exceedingly rich in cement, is really detrimental to the permanence of the concrete. It is well known that neat cement does not resist abrasion well. Again, the richer the mortar or concrete the greater the movements due to variation of moisture content. Not only are these larger movements likely to be a source of trouble in themselves, but the variation in cement content between the skin and the body of the concrete often sets up stresses due to differential shrinkage. A surface skin which is cracked permits the entrance of moisture more easily, and so aids disintegration.

Clearly, then, the surface skin can often be removed with advantage, or alternatively its formation can be prevented. The removal of the skin exposes the aggregate, and, assuming that the latter has been well chosen, there will be a gain, not only in appearance, but in durability. For instance, suppose that of the newly exposed face the projected surface area is made up of 80 per cent. of non-porous aggregate and 20 per cent. of cement. This will be better from the point of view of resistance than a face having 100 per cent. of cement.

Special Cements and Aggregates. A great variety of colours can be obtained by:

1. Using aggregates which contrast agreeably with the cement.
2. Using coloured cements.
3. A combination of (1) and (2).

When coloured cements are used, standard practice for making

good concrete should be followed, and particular care should be taken with all items. Patchiness in colour and/or texture will result from varying proportions, uneven distribution of pigment, variety of gradings and variation of water content. It is foolish, for instance, to pay high prices for coloured cements and special aggregates, and then allow a half-wit on the job to do just as he likes with the water content of the mix. And yet the writer has found many people who appear to work on these lines. Another common case is the man who pays about £10 per ton extra for his cement, and then uses a dirty aggregate because it is two or three shillings a ton cheaper than a clean one. Too often, a cement is expected to cover a multitude of sins—dirty stone, bad mixing, sloppy concrete, insufficient curing, etc. Details on all these points can be found elsewhere.[1]

Since the architectural effect depends on the aggregates it is essential to spend time and care in their choice. There are many shades of limestone available, but often the limestones would have to be used with other aggregates to get desired coloured schemes. There is scarcely any limit to the colours and textures available, and within very wide limits any required effect can be obtained. If very bright colours should be required, then broken coloured glass can be used in place of some of the sand and stone. Some British firms, realising the importance of this work, are now specialising in suitable aggregates, and it is clear that this will extend appreciably in the near future. The shape of the aggregate particles is of importance, particularly if they are to be exposed by merely removing the cement skin. Finally, the grading adopted will influence materially the appearance of the finished surface. For the most durable concrete in exposed situations it is desirable to reduce the amount of cement showing at the face to a minimum, so that care in grading of the aggregate is important. This will also prevent the formation of small pockets.

When making cast stone the size of the aggregate is limited by the character of the natural stone to be imitated and the method of dressing, but for exposed aggregate work there is no such limit. Here, the size of the aggregate is controlled simply by:

1. The requirements for the making of good concrete.
2. The appearance desired.

It is to be noted that this latter finish is a revelation of the concrete—it is not an imitation of some other building material. From this fact alone one can expect more attention being paid to the method in the future.

Having decided on the general colour scheme, it will be advisable to make a series of small sample panels to determine the maximum size of the aggregate, its grading, the colour of the cement, the proportions of the mix, etc., which will give the most acceptable results. All the materials used should be measured carefully so that it will be a simple matter to repeat the chosen finish. This may seem to be an unnecessary expense, but it is not so, and the final results will justify the method. Incidentally, the making of the sample panels will give the workman experience in the execution of the work, and any minor difficulties of application can be adjusted before the work on the structure is taken in hand.

Facing Mixtures. Ordinarily the special mixture used will not go through the full thickness of the concrete. The thickness of the facing, determined according to the conditions ruling, will be fixed, and the rest of the section will be made with ordinary concrete, the idea being, of course, to limit the use of the special material on account of its higher cost. This "two-course" work is suitable for *in situ* or precast work. If the face is made with an aggregate passing a ¼-in. mesh, the thickness need not be more than ½ in. A facing ½ in. to 2 in. thick (according to the work) is satisfactory, so that the extra cost of the facing materials becomes a comparatively small item when considered in relation to the whole structure.

If precast units are made face down, the mix of special aggregates and cement (about 3 : 1) is placed uniformly over the bottom of the mould, and firmly pressed down. Then the backing of ordinary concrete is placed without delay, care being taken not to tamp the backing through to the face of the unit. For units made by the face-up process, the backing is placed to within, say, ½ in. of the top of the mould and levelled off, the top being left rough to give a key for the surface layer. The surface mixture is then added, and the whole of the concrete consolidated by pressure. If the surface is smoothed with a trowel, any pieces of aggregate which become dislodged must be pressed back carefully. A roller will probably be found more satisfactory than a trowel for smoothing the surface.

Skilled Work. It would be misleading to say that anyone who can mix concrete can produce all these finishes. Some of the simpler examples can be obtained by unskilled labour after a little instruction and practice, others require more skill, whilst some of them should only be attempted by experts. For instance, simple

bush-hammering of 6-in. blocks is vastly different from the polishing of an extensive area of walling. In general, then, some degree of skill is necessary, and this point should be appreciated; a man making breeze blocks cannot expect to switch over suddenly and effectively to the production of tooled cast stone.

FINISH WITH UNBROKEN AGGREGATE

Essentially, there are two methods of obtaining this finish:

1. To remove the surface skin after it has formed in the normal process of making the concrete.
2. To prevent the formation of the skin.

The first method may be subdivided under convenient headings, according to the time at which the removal occurs. For instance, the skin can be removed by:

(*a*) Water spray.
(*b*) Scrubbing.

To get special effects with particular aggregates, one can use:

(*c*) Glued face plates.

In the second method, the formation of the skin is prevented by:

(*d*) Treating the forms or moulds with a proprietary material.

Water Spray. The most obvious treatment is to remove the skin before it has hardened. This method, then, does not lend itself to *in situ* work, but it can be adopted very easily for precast products. The way to remove the film of cement from units which have been cast face up is to spray the surface carefully with clean water before the cement has hardened. Generally, pressure, as obtained from ordinary water mains, will be necessary, as sprinkling from a can does not give enough force. The pressure to be used and the period of spraying will vary with different conditions, and they should be determined by experiment. The spraying may be done either whilst the product is in the mould or after it has been removed. The sooner the water spray is used, the easier it will be to remove the cement film, but a few hours must elapse after casting before the spray is used. Too early an application of water under pressure would remove the aggregate as well as the cement. It is better to wait a little too long rather than run the risk of disturbing the aggregate, even though the delay may mean that scrubbing has to be adopted. However, a little practice will soon show the best period to allow for given conditions.

Scrubbing. If the spray is not used within, say, six hours of casting, it will be necessary to resort to scrubbing with a wire or

stiff fibre brush and water. For ordinary work this method should prove effective up to eighteen or twenty-four hours after casting. The forms or moulds should be removed whilst the concrete is still green, as soon as this may be done without injury to the structure, the actual time of removal to be determined by experiment. The correct period to allow will depend upon a number of circumstances—the character of the work, the consistency of the mixture, the weather and the temperature. No definite rule can be given, but it is known that in cold weather the forms must be kept in position much longer than in hot weather, as low temperatures have a retarding effect upon the setting and hardening of the cement. The scrubbing is continued until the surface film of mortar has been removed and the aggregate exposed evenly over the whole area.

Good judgment, which is the result of experience, is needed to determine the proper time to begin scrubbing. If this is begun too soon, unsightly voids may be caused by scrubbing out pieces of large aggregate. If the scrubbing is started too late, the surface will be too hard for brushing to be effective. The deeper the aggregate has to be exposed the earlier the scrubbing must be done. As it is practically impossible to obtain sharp corners in this kind of work, special treatment is indicated. One method is to use rounded moulds at all corners in the formwork so that there are no sharp arrises. Another method is to have a rebated corner and stop the scrubbing at the edge of the rebate ; this gives a sharp arris which is particularly effective.

After the scrubbing, the surface should be washed clean with water and then kept moist for several days. If any pointing is necessary, the defective spots should be patched immediately after the scrubbing. When these patches have hardened (six to twenty-four hours), they should be scrubbed to the same texture as that of the general surface, cleaned with water and kept moist for several days.

Scrubbing of precast blocks and tiles is particularly easy. In the case of tiles, for instance, they can be held over a tank of water, dipped, scrubbed and dipped until the required texture is obtained, and then put in racks for curing.

Obviously the finished surface is rough, but the degree of roughness can be controlled by the size of the aggregate, the nature of the aggregate and the depth to which the mortar is removed. The scrubbing process is not generally used for matching natural stones. It is suggested that the finish obtained has qualities of

its own and that it is a mistake to make it imitate some other finish.

Glued Face Plates. The above methods expose the aggregates in haphazard positions, but the idea may be extended, generally with precast units, to cases where certain aggregates are given predetermined positions. The idea may be merely to ensure that large pieces are at the surface, or the intention may be to arrange them in some pattern or design. The unit is cast face down on a piece of thin cardboard which rests in, and just fills, the bottom of the mould. This cardboard is given a coating of thin glue or shellac and the special aggregate is then placed in position. The interstices may be filled by a sprinkling of finer aggregate, and the mould should then be left for one or two hours to enable the glue to harden. Then a thin layer of cement grout should be brushed over the whole of the material already in position, and the backing placed in the ordinary way. Judicious rodding and tamping will not dislodge the facing aggregate. When the unit is taken from the mould the cardboard can be soaked off if the moisture from the backing has not been sufficient to moisten and loosen the glue. Little, if any, surface scrubbing will be required if this method is adopted, but if it is found necessary the procedure should be as already outlined. If a design is not required the cardboard sheets, already coated with glue, can be dipped in the coarse aggregate and then in the fine aggregate. This method will probably save a little time.

Cement Retarders. Another method of removing the film of cement is to paint the moulds or formwork with a special preparation which delays the setting of the cement at the surface of the concrete. On the removal of the mould or formwork the skin can be readily removed by brushing. The use of one of these materials for architectural work is not always an unqualified success.

FINISH WITH BROKEN AGGREGATE

The word "broken" is used in its broadest sense to cover all cases where portions of the aggregate are removed so as to bring fresh "faces" to view. There are two essentially different cases:

1. Tooling, including bush hammering.
2. Grinding or rubbing, and polishing.

The methods may be applied to precast units or to concrete placed *in situ*.

Cast Stone and in situ Concrete. It is convenient to consider

the various finishes for cast stone, and then extend the methods to the treatment of *in situ* concrete. The methods used for cast stone are applicable to concrete cast *in situ*, since cast stone is merely a special form of concrete. However, there are other problems to solve on account of the difference in working conditions, and these are mentioned later.

Not all precast units would be termed "Cast Stone". For example, many thin tiles are made with treated surfaces for both floors and walls. However, the methods used are essentially the same. The definition of cast stone, prepared by the Cast Concrete Products Association, is given below. It will be clear from this how to differentiate between cast stone and other precast products.

> Cast stone is a structural material intended to be used in a similar manner to, and for the same purpose as, natural stone. It should be manufactured under controlled conditions from carefully selected and graded aggregates and Portland cement. Other descriptions applied to this material are "Reconstructed Stone", "Synthetic Stone" and "Artificial Stone".

Cast Stone. The success of finishes of the types described does not depend merely on the final tooling or grinding. The texture and colour desired can only be obtained by using the correct materials in the correct manner. Good cast stone has the advantages of the natural stone, without the disadvantages.

One is often asked about the desirability of adding sand to the crushed stone. Sometimes it is a mistake, sometimes of no consequence, and sometimes an advantage. The first point to bear in mind is that the grading of the mixed aggregate should be reasonably even from the maximum size down to the very fine material; so that if there is a deficiency of, say, medium-sized particles, the addition of a suitable sand is indicated. The next point to watch is the colour. Clearly there is not much point in using a coarse dark sand as part of the aggregate for reconstructed Portland stone. Thirdly, any sand which is used should be clean and suitably graded. For the majority of reconstructed stones it is unnecessary to add sand to correctly-graded crushed stone aggregate. Occasionally, however, the addition of a sand may be an advantage.

Cast stone is treated [2] by masons or machine tools to produce the same effects as are obtainable in worked natural stone. These processes, which have the effect of removing the surface skin formed in moulding and the exposure of the uniform mixture of cement and aggregate used, are likely to be most satisfactory. It is also possible to impart a texture to the cast stone before it has matured

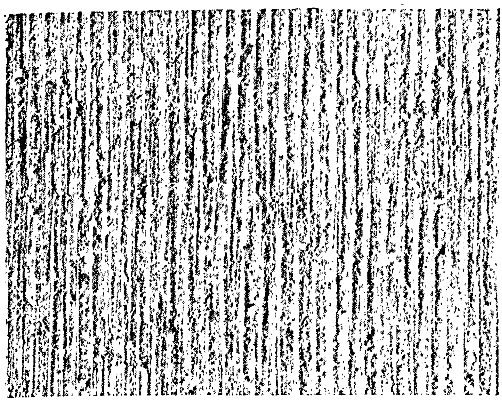


Fig. 10.—Cast Stone Finishes

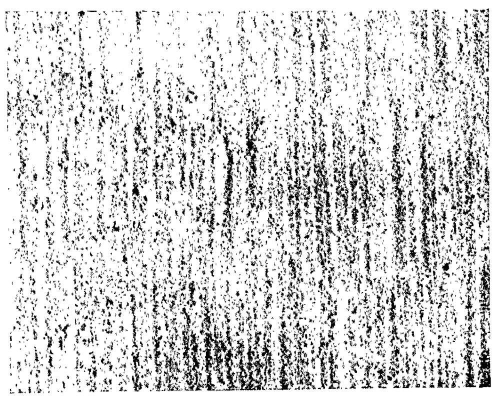
Masoned Cast Stone

(A) Tooled.
(B) Boasted.
(C) Bush-hammered.

(A) Tooled.

Typical examples of cast stone finishes included in the Cast Concrete Products Association Exhibit at the Building Centre.

[See also (D) and (E).]



(B) Boasted.

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(C) Bush-hammered.

Fig. 10.—CAST STONE FINISHES

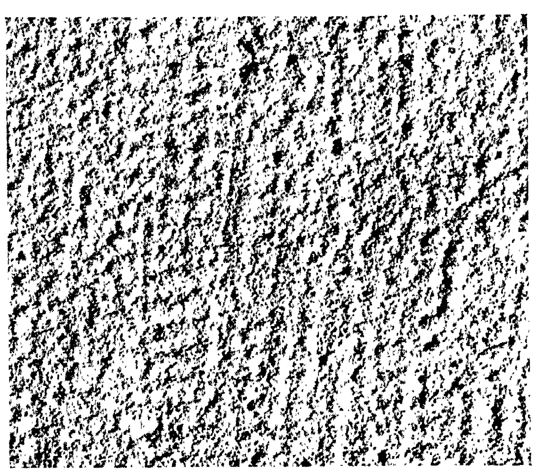
Masoned Cast Stone

(D) Rubbed.

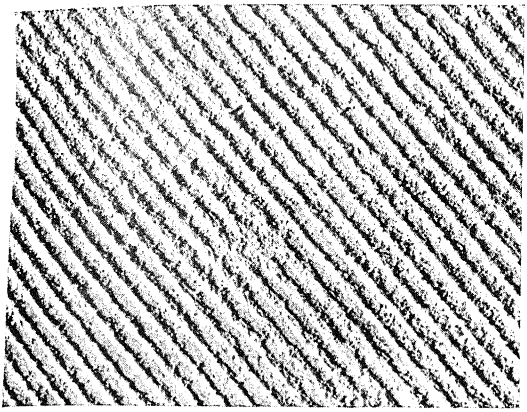
(E) Sparrow-pecked.

(D) Rubbed.

Further typical examples of Cast Stone finishes included in the Cast Concrete Products Association Exhibit at the Building Centre.



(E) Sparrow-pecked.



(A) Dragged.

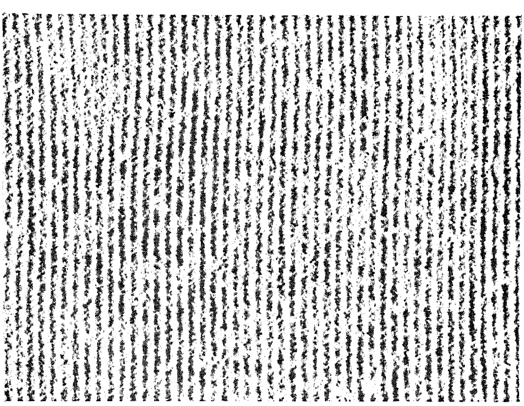
Fig. 11.—Cast Stone Finishes

Surfaced Cast Stone

(A) Dragged.
(B) Etched.
(C) Combed.

Typical examples of cast stone finishes included in the Cast Concrete Products Association Exhibit at the Building Centre.

(B) Etched.



(C) Combed.

by combing with steel scrapers, etc. Reproductions of the typical effects are given in Figs. 10 and 11, but these do not represent the wide range of cast stone available or the variety of each of the named finishes.

Masoned Cast Stone. Unfortunately there is likely to be misunderstanding from time to time on account of the two uses of the word "tooling". Many people refer to the surface treatment of cast stone or concrete with mason's tools as "tooling". It will be seen from Figs. 10 and 11, however, that the Cast Concrete Products Association use the word "masoned" for the group of finishes, keeping the word "tooled" for one particular type of finish. It is felt, however, that many will continue to use the word "tooled" in its wider significance.

Natural stone has been finished with mason's tools for centuries, and the method is quite familiar. The tools used are the mason's boaster and a wide chisel with serrated teeth. A chisel can be obtained with several replaceable "sets" of teeth. No aggregate larger than $\frac{1}{4}$ in. should be used, as large pieces are apt to be dislodged by the chisel, leaving a pitted surface. Also, the concrete should be dense and contain no air or water holes. The concrete must be fairly hard before tooling is commenced so that the surface may be sharp and clean cut. On the other hand, it is unwise to wait until the cement has become extremely hard, as the labour of tooling will be unnecessarily increased.

Bush Hammering. Bush hammering is rarely used for precast units, whereas it is fairly common for *in situ* concrete. This method, therefore, will be described later. It could be used with good effect where concrete blocks were required to match some *in situ* concrete which had been bush hammered.

Rubbing, Grinding and Polishing. Here again there is likely to be misunderstanding concerning the finish, as these three words are used indiscriminately to describe finishes which have had the surface removed by carborundum (or other suitable means) to present a smooth finish. Perhaps the best way to use these words is to consider that "grinding" is extensive "rubbing" and that "polishing" is a refinement or subsequent treatment of either.

Rubbing. Rubbing is specially suitable for high-grade work where very sharp arrises are required. When cast stone is taken from the moulds there are often small air holes on the surface. These and any other irregularities there may be must be filled with a mixture similar to that used for the facing. Then a cream, made of finely crushed stone and cement, is floated over the whole

of the surface. When dry, the surface is brushed, and the result, which is a sand-faced finish, is acceptable to many people. For the rubbed surface, the concrete must be left until it is harder. If possible, the hardness of the cement should approximate to that of the aggregate so that one is not rubbed away before the other. Carborundum is chiefly used for rubbing down, but York stone and red Mansfield stone are suitable. Plenty of water must be used, the cement paste which works up being removed with a brush and clean water.

Polishing. As already mentioned, this treatment is a refinement of rubbing. For work done by hand, snakestone is generally used to obtain the final polish. For mechanical finishing, the use of fine discs on the machine will generally give the desired polish without further treatment. This finish is used for cast Hopton Wood stone and terrazzo tiles.

IN SITU CONCRETE

There is literally no limit to the ways in which cements and aggregates can be blended to produce exposed aggregate finishes. The surface can be made to imitate reconstructed stone, or it can have an individuality all its own. Colours, shapes, sizes, design—all these can be modified in endless ways, as a little experimenting will show.

There is a connection between the structural design of a concrete bridge, for instance, and the kind of finish to be adopted, since the question of cover to the reinforcement has to be considered. On the soffits of beams and slabs an extra $\frac{1}{2}$ in. of cover is desirable if there is to be bush hammering or acid treatment.

For a large area, it will add greatly to the appearance of the structure if the surface is broken up by courses, or into panels. Concreting should stop only at these courses, as it is impossible to join new work on to set concrete without the joint being visible.

As in the case of the precast units, it is unnecessary to use the facing mixture throughout, and appreciable economies can often be effected by having a facing of, say, 2 in. and a backing of ordinary concrete. However, some coloured cements are comparatively low-priced, and it may be cheaper to use them throughout the whole thickness of wall panels (4 in. or 6 in.) than to (*a*) provide a key and apply a finish later, or (*b*) use two mixes at the same time.

Masoned Finish. As with precast work there is a looseness when using the word "tooling", so, to avoid misunderstanding,

the word "masoned" will be used in the same way as before—it does not include bush-hammering. Boasting should be done as soon as possible after the removal of the sheeting, unless the aggregate is particularly hard.

Bush Hammering. Bush hammering not only exposes the aggregate (as in the scrubbed finish) but cuts it as well. This gives a sparkle to the surface, due to the light-reflecting properties of the newly-exposed faces, and produces a finish quite different from that obtained by scrubbing, even though the same aggregates are used. The breaking of the particles of stone does not weaken the concrete at all. Bush hammering is particularly suitable when an "exposed aggregate" effect is desired, but when the shuttering cannot be removed for several weeks, so that the concrete is quite hard. In fact, this treatment should not be used until the concrete has hardened thoroughly, say, for at least six weeks for ordinary Portland cement and ten days for rapid-hardening Portland cement. If the work is done too soon, some of the pieces of aggregate, instead of being merely broken, may be removed entirely, thus causing unwanted pits in the surface.

The desired effect may be obtained by hand or by mechanical means. The hand tool usually has a face about one inch square cut into nine or sixteen broad-based teeth. In general, either method may be used, but if the corners must be bush-hammered, they should be done by hand. However, corners are always difficult, as it is almost impossible, at such places, to prevent chipping out pieces of concrete, thereby leaving ragged and unsightly edges. Two methods of dealing with this difficulty can be used. The surfaces at the corners can be given a "rubbed finish" and the hammering stopped at a sufficient distance from the corners to leave a smooth margin of a width that will be in scale with the panel that is being bush-hammered. This consideration often leads to laying out the panels in such sizes as will be best fitted for treatment by hammering. Another method is to eliminate sharp corners completely and to round off the edges by hammering. This, however, is seldom suited to architectural designs on account of the comparatively large amount of material it is necessary to remove to obtain a uniformly rounded corner.

Rubbing. A rubbed finish is one of the least expensive of the durable surface treatments. The forms are removed as soon as possible, and immediately this is done the surface of the concrete should be wetted thoroughly and rubbed with a No. 20 carborundum stone. If done soon enough, this rubbing will remove minor

blemishes such as nailhead marks and board marks, but it will not obliterate all the irregular marks between the boards. Whether these latter marks can be removed or not depends on the care which was expended on the construction of the formwork and on the amount of rubbing which it is proposed to do.

A mortar paste will work up on the face of the concrete and it should be removed by washing and brushing. If the concrete has been well placed there will be no large cavities in the surface, but there will be a number of small voids which should be filled with mortar. A suitable mortar can be made with two parts by volume of fine sand (taken from the supply used for making the concrete) and one part of cement. This mixture is worked into the face with the carborundum blocks so that an even, regular face is obtained. Care must be taken not to leave an appreciable thickness of slurry or mortar on the face, as this would defeat the whole object of the treatment. It should be realised that the idea of rubbing is to remove excrescences, fill voids and partially expose the aggregate (not cover it). Apart from not getting the desired appearance, a coating of mortar will give trouble later by peeling and cracking.

If this first rubbing is not done whilst the concrete is still green, the labour will be increased. In such a case it may be necessary to remove fins, etc., by chisels or bush hammers, following this by the carborundum stones which can be helped by a cement slurry over the whole of the surface (after thorough wetting). With this delayed treatment it is even more important that a thickness of slurry should not be left on the concrete.

A second rub is given when the concrete is several months old, and is therefore quite hard. Carborundum blocks (No. 24 this time) and water are used, and the paste should be removed by washing and brushing, as before.

This finish is serviceable and comparatively cheap, but it must be appreciated that it does not necessarily remove all board marks.

Grinding. Grinding, as already stated, can be regarded simply as intensified rubbing. Mechanical means are employed, and a greater thickness of concrete is removed, so that in this method all marks can be eliminated (assuming good formwork and good concrete practice throughout the work).

Polishing. This is really an additional treatment for rubbed or ground finishes, although, as mentioned above, it is often taken to mean grinding. A good finishing polish consists of equal parts of beeswax and turpentine. Before using such a polish the surface

should be cleaned thoroughly and allowed to dry. To get really good results, it is advisable to adopt the procedure used when finishing terrazzo.[3]

Mixed Finishes. Interesting architectural effects can be obtained by using two or more finishes on the same job. For example, a rubbed wall face with bush-hammered panels, a polished face with different aggregates and different coloured cements, etc. A simple example is a reeded surface, the projecting fins of which have been ground to reveal the aggregate.

FLAGS

Limestone for Structures and Products. Consideration of the information given in the preceding chapters indicates that limestone concrete can be used effectively for all kinds of structures and precast units. The illustrations appearing in this volume show some of the jobs which have been carried out successfully. A comprehensive list of the possibilities would be both tedious and unnecessary since the uses of limestone concrete can be stated quite briefly: where concrete is required, limestone can be used with safety, often with economy, and always with complete satisfaction. Even when, owing to the distance between the job and the quarry, the limestone aggregate proves more expensive than other aggregates, it will often be found advantageous to use it on account of its many good qualities.

Space prevents the detailed description of even the groups of uses for limestone, and attention will be confined to three items, i.e., flags, sewers, and roads. It cannot be stated too strongly that limestone as supplied by members of the British Limestone (Roadstone) Federation—and therefore of approved quality—is suitable in every respect for flags, sewers, and roads. Flags are considered in this chapter, and sewers and roads in the two next chapters.

Specification for Flags. British Standard Specification No. 368—1936 [1] for "Pre-cast Concrete Flags" lays down the requirements for good flags, and it is generally considered that flags complying with this specification are satisfactory.

The requirement for aggregate is stated quite briefly:

> The aggregate shall be approved by the purchaser. When required, a sample of the aggregate shall be submitted to the purchaser with the tender. The whole shall pass a B.S. $\frac{3}{8}$-in. mesh test sieve.

Sample flags have to comply with the three tests given below.

> (*a*) *Test for Transverse Strength.*—When tested in the manner described in Appendix A, flags 2 in. thick shall support for at least one minute a total load of not less than 1,232 lb. for each foot of width, and flags $2\frac{1}{2}$ in. thick shall support for at least one minute a total load of not less than 1,904 lb. for each foot of width.
>
> (*b*) *Test for Rate of Wear.*—When tested in the manner described in

TESTS OF FLAGS BY STANGER

Marking	Thickness	Tests			
		Transverse lb.	Wear lb.	Absorption Per cent.	
				10 min.	24 hr.
DU	2 in.	1,720	0·78	1·16	4·71
		1,720	0·90		
		1,930			
		1,950	0·84		
		1,830			
DU	2½ in.	2,520	0·87	0·97	4·82
		2,380	1·30		
		2,960			
		2,520	1·085		
		2,595			
DW	2 in.	2,110	0·83	1·18	5·04
		2,100	0·87		
		2,130			
		1,580	0·85		
		1,980			
DW	2½ in.	2,740	1·25	1·04	5·05
		2,920	0·94		
		3,290			
		2,440	1·1		
		2,848			
VU	2 in.	1,970	1·00	0·84	3·78
		1,470	0·88		
		1,560			
		1,990	0·94		
		1,748			
VUA	2½ in.	2,090	1·07	1·4	5·2
		2,210	0·65		
		2,040			
		2,070	0·86		
		2,102			
VW	2 in.	2,110	0·70	1·15	4·34
		1,720	0·86		
		1,610			
		1,760	0·78		
		1,800			
VW	2½ in.	2,410	1·05	0·97	3·84
		2,750	1·05		
		3,100			
		2,480	1·05		
		2,685			
B.S.S. for 2-in. flag		1,232	1·50	2·50	6·50
B.S.S. for 2½-in. flag		1,904	1·50	2·50	6·50

Appendix B, the wear on the face of a sample shall be uniform in character and shall not result in a total loss in weight of more than $1\frac{1}{2}$ lb.

(*c*) *Test for Absorption of Water.*—When tested in the manner described in Appendix C, the increase in weight by absorption of water in the first ten minutes shall not exceed 2·5 per cent. of the dry weight of the test piece and the total absorption shall not exceed 6·5 per cent. of the dry weight.

Tests of Flags. In 1938 tests were carried out by R. H. Harry Stanger, Assoc.M.Inst.C.E., on several flags made with limestone as the aggregate. Four different gradings were used (from two different parts of England) and both 2-in. and $2\frac{1}{2}$-in. flags were tested, so that there were eight sets of results. The results of the transverse tests have already been given in Chapter V, but for convenience all the results obtained are given here. In a letter sent on 18 October, 1938, Mr. Stanger said that, in his opinion, the results of the tests on the slabs compared very favourably with the general run of paving slabs submitted for test.

SEWERS

Use of Concrete. The merits of concrete pipes for the conveyance of sewage are widely recognised, and proof of this can be found in the success of the concrete pipe industries which exist in all parts of the world. Concrete has also been used successfully for many years in the construction of monolithic sewers of various sizes.

To give satisfactory service, a pipe forming part of a sewage system should possess: durability, smooth internal surface, resistance to attrition, strength under external loading, ease and reliability of jointing, ease of handling and rapidity of laying, and low prime cost. Concrete pipes satisfy these requirements to a remarkable degree. In fact, it may be claimed for concrete that in normal circumstances it gives better service at less cost than any competitive material. Concrete pipes are true to gauge, and being as a rule 6 ft. to 8 ft. long have fewer joints, thus possessing a higher coefficient of discharge.

Sometimes, however, special conditions arise which need to be taken into consideration, and the following notes have been taken from *Concrete Pipes and Conduits* issued by the Cement and Concrete Association.

SPECIAL CONDITIONS[1]

Sulphate Salts. In a few localities sulphate salts—notably magnesium and calcium sulphate—are known to occur in clay soils. There is at present no general agreement on what the limit is beyond which sulphate concentrations in clay may become dangerous to Portland cement concrete. Previous experience in the district should be taken into consideration. It should be remembered, however, that cases of failure may have been due at least in part to bad workmanship, and that denser concrete might not have been similarly affected.

The attack can usually be recognised in the early stages by the weakness of the concrete and the presence of white deposits within it. The action which takes place depends not only on the degree of concentration of the sulphates and on the porosity of the concrete,

but also on the extent of erosion by flowing water in removing the products of corrosion and exposing fresh surfaces to attack. If concrete were absolutely impervious, attack by sulphate salts would be relatively low. Consequently, when the laying of Portland cement concrete pipes is contemplated in any of the few "sulphate" districts in this country the first essential is to select a pipe in which the concrete is as dense as possible. Concrete pipes that are practically impervious may now be obtained, showing an increase on dry weight of less than 2 per cent. under absorption test as against the maximum value of 6·5 per cent. allowed by B.S.S. No. 556—1934.[2] In severe cases the alternatives are either to use a pipe made with aluminous cement, which is less affected by sulphates, or to protect the surface of Portland cement pipes with some material inert to sulphate action.

Acid Sewage. It is important to note in connection with sewer schemes that high concentrations of sulphuretted hydrogen or sewer gas, which may arise from septic sewage, have been known in the presence of oxygen to corrode unwetted portions of Portland cement concrete sewers, particularly in hot climates; but cases where this has occurred in this country are extremely rare. In a properly designed sewerage system the flow should be such that the sewage reaches the outfall before putrefying; or where non-cleansing velocities of flow are unavoidable sufficient ventilation should be provided to prevent the accumulation of gas.

Porous concrete is attacked by such acids as sulphuric, lactic and carbonic, and by the various acids found in fruit drinks. Large quantities of acid trade wastes discharged into a concrete sewer might cause damage in the absence of an acid-proof bitumen or other lining to the sewer in the vicinity. In general, however, the excess of ordinary domestic sewage, which is alkaline in character, neutralises any acids that may enter the sewer from the kitchen and trade wastes. For special cases concrete pipes may be obtained in sizes up to 72 in. diameter with hard and acid-proof bitumen linings.

Hard, Soft and Acidic Waters. Hard waters containing appreciable quantities of dissolved lime salts have little or no effect on good concrete. Humic acid arising from the decay of peat has little action on Portland cement concrete, but waters which, because of their brownish colour, would be described as peaty are often very soft and contain carbonic acid. The effect on good concrete is usually limited to surface action of limited duration owing to the formation of a skin which protects the concrete. The same may

be said of the leaching effect of pure natural waters draining from certain moorland areas, and provided the concrete is well-made and dense serious trouble is unlikely.

Contaminated Ground. Chemical attack on Portland cement concrete may occur on sites formerly occupied by factories, or in made ground contaminated with trade wastes. The processes used in a factory may suggest the type of contamination which may be present on the site. Such contamination may be quite harmless, but sites of disused gasworks, or ground filled with clinker, ashes or refuse should be regarded with suspicion, and be investigated.

LIMESTONE AGGREGATE

A good quality limestone which is structurally sound is quite suitable as an aggregate for concrete for all ordinary drainage work. In exceptional circumstances the concrete, as indicated above, may be liable to attack, but it is not always realised *that the cement, and not the limestone, is the weak link.* The following details will be found helpful.

Compressive Strength. As far as compressive strength is concerned, it can be stated without reservation that the strength of limestone concrete can be made as high as may be required by any modern specification. The strength of the limestone is appreciably greater than the strength of the concrete in which it is used, so that the better the cement and the workmanship the higher the results will be.

To avoid repetition reference should be made to Chapter IV, " Compressive Strength of Concrete ". From the figures given it will be seen that strengths higher than 7,000 lb. per square inch at 28 days can be obtained. The results, which are typical of those which can be procured with numerous good limestones, are sufficient proof that limestone is perfectly satisfactory as a coarse aggregate for concrete sewers as far as compressive strength is concerned.

Porosity. It is generally agreed that, as far as permeability is concerned, curing conditions are more important than variations in the aggregate. To make watertight concrete is largely a matter of good workmanship, and to make a watertight concrete structure this good workmanship must be accompanied by good design. The passage of water through concrete can be prevented by following certain rules irrespective of the nature of the coarse aggregate, assuming that clean, structurally sound material is used.

Chapter VI, " Watertight Concrete ", deals with this problem

of watertight concrete, giving simple rules which should be followed to ensure good results. It is probably safe to say that leakage in a structure occurs through cracks or faulty joints rather than through the concrete itself. As already mentioned, cracks and joints can be controlled by good design and good workmanship, but it should not be overlooked that the use of limestone aggregate is an advantage since the moisture movement of concrete made with it is less than that of any other concrete.

Abrasion. The question of abrasion is not an easy one, as there is a popular impression that the resistance to abrasion of concrete depends essentially on the resistance to abrasion of the coarse aggregate. Whilst it is not suggested that the coarse aggregate has no effect, its effect is nothing like as great as is commonly supposed. Though there is still much to be learned concerning the wear of concrete, it seems to be universally agreed that the wear of the aggregate, as demonstrated by the attrition tests, is not necessarily a measure of the wear of the concrete made with that aggregate.

One of the recognised tests for determining the wear of a road stone is the attrition test. This was arranged originally to determine the rate at which wear would occur in a material used for macadam roads subjected to the grinding action set up under the pressure of iron-tyred wheels. The percentage of wear is obtained, and from this a figure known as the " French coefficient " is deduced. It is defined by the relation

$$\text{French coefficient of wear} = \frac{40}{\text{percentage of wear}}.$$

In the proposed standard specifications for monolithic concrete sewers prepared by the American Concrete Institute [3] in 1923, it was suggested that crushed stone used as the coarse aggregate should have a French coefficient of wear of not less than 8. There is no doubt that a good limestone would comply with this condition quite easily, and the paragraph was only intended for use in districts where stones of questionable value were common. Quite apart from this, however, it is suggested that the hardness of the coarse aggregate should not be used as a basis for determining its suitability for concrete. It is far better, if there is any doubt, to test the concrete itself for abrasion. Not only is this a fair test, but it gives information which is really valuable. Such tests could be made as described in the British Standard Specification for Concrete Flags, No. 368—1936.

Chemical Action. Here, again, the question of making concrete resistant to chemical action becomes merely a problem of making good concrete. Assuming, as always, that the coarse aggregate is structurally sound, it will be found that any disintegration which may occur will be the result of attack on the cement rather than on the aggregate. For a discussion of this, see Chapter VIII. It is pointed out that the most important thing of all is to make concrete which is watertight everywhere.

Comment. The position boils down to this, therefore, that limestone concrete can be assumed to be as resistant as any other kind of concrete. As far as sulphates, trade wastes, septic sewage, etc., are concerned, their effect on limestone concrete will be the same as on any normal concrete.

CHAPTER XII

CONCRETE ROADS

ALL-CONCRETE SLABS

Wear. Quite apart from laboratory tests, judgment must ultimately be made on the performance of the road itself, and the details given in this chapter show conclusively that limestone concrete will stand up to wear as well as any other concrete.

Slipperiness. An objection sometimes raised to the use of limestone is that it forms a slippery surface. This argument is probably the result of a statement made by someone who has seen the effect caused by a very soft limestone or chalk. Such an aggregate cannot be compared with a structurally sound limestone, and all the available evidence points to the fact that a good limestone concrete is no more slippery than concrete made with any other aggregate. If a limestone concrete is found to be slippery it may be that this state of affairs has been brought about by having the surface finish too smooth, and it is a question of the making of the concrete rather than one of the aggregate used.

It may be mentioned [1] that very few concrete roads having an unsatisfactory resistance to skidding have been brought to the notice of the Ministry of Transport, and that in each of these cases it has been found that the surface of the road contained an unduly high proportion of sand and cement and a correspondingly low proportion of coarse aggregate. This condition probably results from excessive tamping given at the time of construction in order to ensure that the concrete should be dense and its surface free from irregularities. The fine texture due to the presence of too much cement and sand in the surface renders the concrete liable to wear smooth under traffic.

Compressive Strength. As the compressive strength of concrete is still, in a large number of cases, the property by which concrete quality is measured, it is necessary to have sufficient strength to meet all specifications. There is no difficulty at all when limestone is used as the aggregate. For details of the compressive strength of limestone concrete, reference should be made to Chaper IV.

Flexural Strength. In Bulletin 7 [2] of the National Crushed Stone Association, Inc., Goldbeck draws certain conclusions as the result of investigations made to develop a method for the design of concrete having any desired modulus of rupture. Some of these conclusions are given below:

1. In concrete roads the property of high resistance to cross-bending, as expressed by the term "modulus of rupture", is of paramount importance.
2. A wide range in modulus of rupture is produced in 1 : 2 : 3½ concrete due to the characteristics of the coarse aggregates.
3. There is no definite relation between crushing strength and modulus of rupture of concrete when different coarse aggregates are used. Weak aggregates may produce concrete of high compressive strength but very low beam strength.

It is shown in Chapter V, that limestone concrete gives particularly good results in flexure. This is a point of the utmost importance in road work, where high bending strength is of undoubted value.

Other Properties. As in other types of structural work, concrete for roads should be reasonably watertight, and should also be durable. These properties are discussed in detail in Chapters VI and VIII. Limestone concrete satisfies all requirements.

CEMENT-BOUND MACADAM

In the paper entitled "Research and Its Influence on Design", submitted to The Hague Congress by the British Reporters in 1938, was the following section headed "Cement-Bound Macadam".

A considerable mileage of these roads has been laid since the last Congress, mostly by the sandwich method, and almost without exception the roads existing four years ago are still in excellent shape to-day.

This construction, on account of its rugosity, has been used with success where steep grades exist and where horse traffic is plentiful. Thus, they are to be found in the hilly districts of Lancashire and the North.

Where suitably hard aggregates can be obtained locally the cost of construction and maintenance is remarkably low. Thus in Gloucestershire a road laid in 1934 with a local limestone cost about 2*s.* 6*d.* per square yard, and the maintenance costs since have been nil.

Hitherto, granite, basalt, whinstone or limestone have been deemed the most suitable types of stone to employ, but in some cases recently a softer stone has been used on the bottom 2 in., the top being of the more acceptable stone.

EXAMPLES

No matter how many arguments are put forward to show that a particular kind of concrete is satisfactory, the practical man will not be satisfied until he can see the results of actual tests on the structures concerned. The reports given below, therefore, on three experimental lengths of road are both interesting and enlightening.

Gloucester-Newport Road. Experimental concrete sections [3] were constructed in June, 1932. Sections were laid to compare concrete made with Frampton gravel, Clee Hill granite, Malvern granite and local mountain limestone, the slabs being in each case 9 in. thick and reinforced with a single layer of high tensile steel weighing 5½ lb. per square yard. The Frampton gravel was mixed with cement in the proportion of 4½ : 1, whilst the mixes used on the other three sections contained 3 parts of aggregate, 1½ parts of Holm sand and 1 part of cement. All four sections are in excellent condition and no difference is to be observed in their behaviour.

All the aggregates [4] are capable of providing a satisfactory running surface.

Dock Street By-Pass, Newport, Mon. This experiment was undertaken [5] in view of the freedom from cracking of two-course 9-in. unreinforced concrete laid in the City of Cardiff. In this work limestone up to 2-in. gauge is used in the top course, and the slabs are 12 ft. long. It was decided to investigate whether the freedom from cracking was attributable to (*a*) the length of the slabs or (*b*) the use of large aggregate in the surface.

The road was inspected in March 1937, when all three sections were in good condition generally. The running surface was excellent but slight spalling was noticed at some of the joints. All the sections have so far given quite satisfactory results without cracking.

The number of sections [6] included in the experiment is not sufficient to enable the influence of all the variables involved to be determined, but the results show that if unreinforced concrete is laid in 12-ft. slabs, a comparatively cheap construction (viz., single-course 9-in. concrete of a 4 : 2 : 1 mix, with dolomitic limestone of either ¾-in. or 2-in. maximum gauge) can be used without cracking.

The freedom from cracking in the 9-in. concrete in 30-ft. slabs using dolomitic limestone aggregate is interesting as compared with the extensive cracking of the 8-in. concrete in 30-ft. slabs using ¾-in. gravel aggregate at Harmondsworth.

Maghull Diversion, Lancashire. The road has been inspected [7] at intervals, the latest inspection being made in April, 1937.

The surface of the concrete was uncracked and in excellent condition. The only section which could be said to differ from the others was Section L, in which limestone aggregate was used, which was slightly lighter in colour.

One of the objects [8] was to compare the relative merits of single-course work and two-course work with cheaper aggregate in the bottom than in the top course. The results of this experiment are in agreement with those obtained elsewhere, viz.:

There is no advantage to be gained by using two-course instead of single-course concrete.

Satisfactory results can be obtained with a variety of aggregates, including granite, limestone and gravel.

A 4 : 2 : 1 mix in the running surface gives satisfactory results.

There is no justification in ordinary circumstances for a more expensive surfacing than concrete 8 in. thick, 4 : 2 : 1 mix, doubly reinforced.

Comment. The evidence given in this and other chapters shows clearly that good, structurally sound limestone is entirely suitable for both slab roads and cement-bound roads. The limestone can be used in both courses in two-course work, or throughout the slab in single-course construction. As far as aggregate supplies are concerned the essential point to watch is the quality; the limestone should be well-graded, structurally sound material from an approved source. With such an aggregate, assuming good design and workmanship, an entirely satisfactory road is assured.

CHAPTER XIII

CONCLUSION AND ACKNOWLEDGMENT

Conclusion. It will be seen from the foregoing information that good limestone is an excellent aggregate for concrete, particularly where a high degree of fire resistance is required. In many instances the use of limestone will be found to stimulate local trade, and, at the same time, give the desired results with less expense.

A company wishing to sell a high-class aggregate must be prepared to supply the user with a product on which he can count in every way. Some of the points to be watched have been discussed in these notes. The writer understands that The British Limestone (Roadstone) Federation is making a special point of giving all these matters its most careful attention, so that anyone using limestone aggregate will have a service second to none. It is not the intention to sell limestone by belittling competitive products, but on a sound basis of quality and service.

Acknowledgment. In the preparation of these notes use has been made of the writer's articles mentioned below, and he wishes to acknowledge his indebtedness to the editors and publishers of the journals concerned:

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Illustrations

Fig. 1. Photo by courtesy of Messrs. F. J. Moore, Ltd.

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